ARCTIC CLIMATE THREAT
Methane from Thawing Permafrost

SPECIAL PHOTO ESSAY
Microscopic Life Up Close

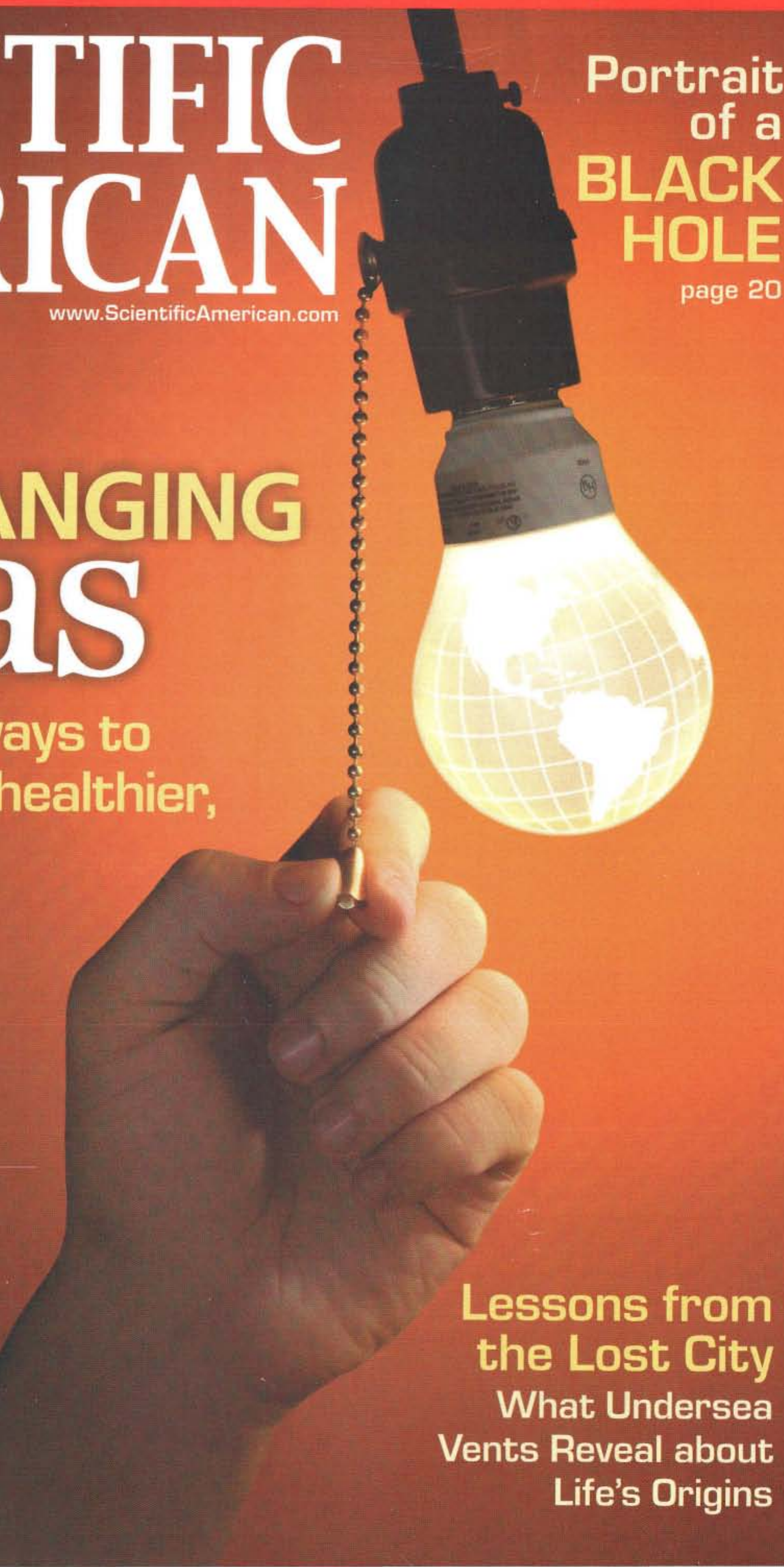
SCIENTIFIC AMERICAN

December 2009
www.ScientificAmerican.com

Portrait of a BLACK HOLE
page 20

WORLD CHANGING Ideas

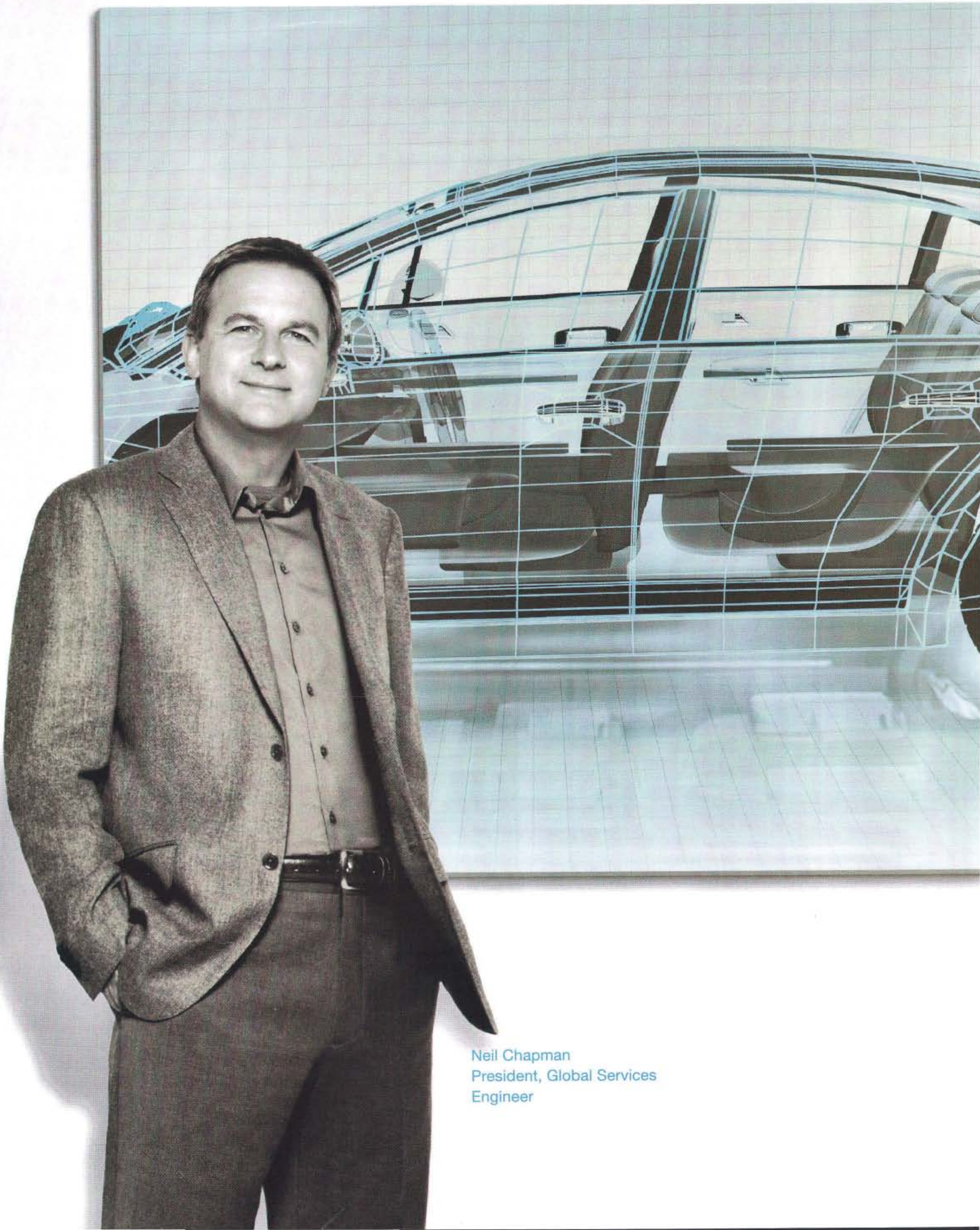
20 innovative ways to build a cleaner, healthier, smarter world



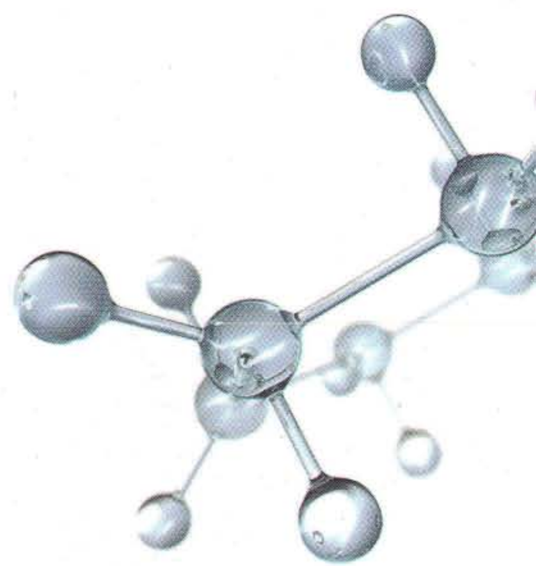
Ancient Greek Computer
Sophisticated Technology Tracked the Heavens

Lessons from the Lost City
What Undersea Vents Reveal about Life's Origins

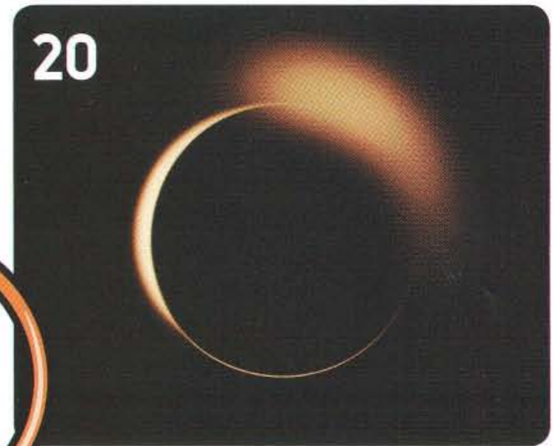
$5.99 U.S. U.K. £4.10



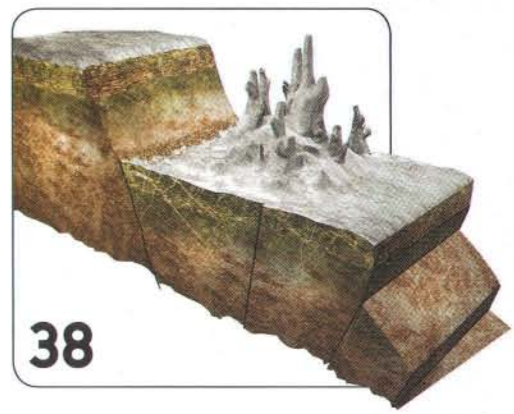
Neil Chapman
President, Global Services
Engineer

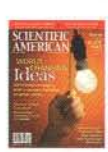


SCIENTIFIC AMERICAN December 2009 • Volume 301 Number 6



28

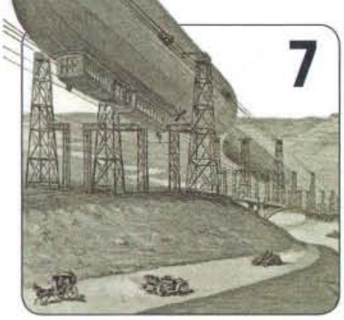


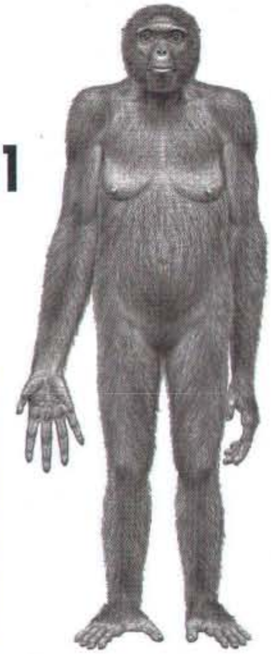


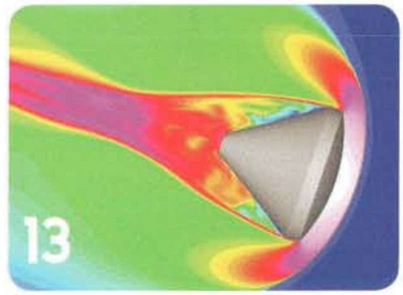
ON THE COVER

Innovative ideas in the areas of energy, transportation, environment, electronics and robotics, and health and medicine.
Image by Cary Wolinsky.

CONTENTS DEPARTMENTS







GO TO SCIENTIFICAMERICAN.COM

The 2009 Nobel Prizes

Explore the prizewinning break-throughs—from unraveling the inner workings of the life-enabling ribosome to inventing the sensors used in digital cameras—some of which were chronicled by the Nobelists themselves in *Scientific American*.

AP PHOTO (*Nobel medal*)

More at **www.ScientificAmerican.com/dec2009**

Scientific American (ISSN 0036-8733), Volume 301, Number 6, December 2009, published monthly by Scientific American, Inc., 75 Varick Street, 9th Floor, New York, N.Y. 10013-1917.

Periodicals postage paid at New York, N.Y., and at additional mailing offices. Canada Post International Publications Mail (Canadian Distribution) Sales Agreement No. 40012504. Canadian BN No. 127387652RT; QST No. Q1015332537. Publication Mail Agreement #40012504. Return undeliverable mail to Scientific American, P.O. Box 819, Stn Main, Markham, ON L3P 8A2. **Individual Subscription rates:** 1 year $39.97 (USD), Canada $49.97 (USD), International $61 (USD). **Institutional Subscription rates:** Schools and Public Libraries: 1 year $69 (USD), Canada $74 (USD), International $81 (USD). Businesses and Colleges/Universities: 1 year $299 (USD), Canada $304 (USD), International $311 (USD). Postmaster: Send address changes to Scientific American, Box 3187, Harlan, Iowa 51537. **Reprints available:** write Reprint Department, Scientific American, Inc., 75 Varick Street, 9th Floor, New York, N.Y. 10013-1917; (212) 451-8877; fax: (212) 355-0408. **Subscription inquiries: U.S. and Canada (800) 333-1199; other (515) 248-7684. Send e-mail** to sacust@sciam.com Printed in U.S.A.

Wanted: Bright Ideas

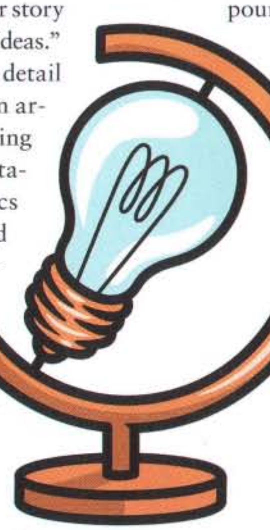
One of 100 billion nerve cells in the human brain, the neuron waits, ready. Suddenly, a neighbor releases signaling molecules with an attention-getting message, like the irresistible chatter of a next-door gossip who has a hot tidbit. The receiving cell, excited, experiences fluctuations in ion concentration, creating a small electric current flow. Then it, too, releases communication signals down the line. The cascade continues until a large region of the brain is buzzing with heightened processing. Imaging scans would reveal the additional blood flow and electrical activity as thousands of neurons flare in response.

A good idea can be like that—it stirs everything up—whether it is being shared throughout a network of cells in one person's brain or in the world at large, through a community of people. Good ideas motivate us to action. They lead us to reflect on how to make things better. They spur us not to settle only for what is possible today.

That is why we are celebrating a set of innovative projects with our cover story for this issue, "World Changing Ideas." In this new annual section, we detail 20 ways to push the frontiers in areas that are critical to improving modern life: energy, transportation, environment, electronics and robotics, and health and medicine. Some of the inventions are dazzlingly simple—such as how SolarCity, headquartered in California, removes the biggest obstacle to solar-panel installations by homeowners: their upfront cost. Some are head-thumpingly obvious in hindsight, such as employing zoning to thwart the currently nearly uninhibited resource depletion of the world's oceans. (For more on that topic, see Perspectives, on page 16.) And some, such as Hewlett-Packard's Central Nervous System for the Earth, a planned array of up to a trillion pushpin-size sensors for the globe, are mind-bendingly sophisticated in their scope and potential implications.

All the concepts in this section inspire hope that advances in science and technology will keep improving our lives in the years ahead. Turn to page 28, then, for a look at the future.

One place where humanity's creative problem-solving abilities are in high demand is in the battle against global climate change. While government policy leaders debate their countries' responses to this phenomenon, it continues to disrupt ecosystems with unsettling speed. As Katey Walter Anthony describes in "Methane: A Menace Surfaces," her feature article starting on page 44, thawing Arctic permafrost is doing more than causing damage by heaving and cracking the foundations of buildings: it is also creating lakes that emit methane, a gas that, pound for pound, has more than 20 times the heat-trapping power of carbon dioxide. These new methane emissions could accelerate the process of global warming. Walter Anthony's research serves as yet more evidence for the great need to address this problem. But will we act on our ideas in time? ■



MARIETTE DiCHRISTINA
acting editor in chief

ETHAN HILL (*DiChristina*); CHRISTOPH NIEMANN (*illustration*)

SCIENTIFIC AMERICAN®

Established 1845

Letters to the Editor

Scientific American
75 Varick Street, 9th Floor,
New York, NY 10013-1917
or editors@SciAm.com

Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article instantly at www.ScientificAmerican.com/sciammag

LETTERS

editors@SciAm.com

Nukes ▪ Neandertals ▪ GM Crops

AUGUST 2009

> **"In a parallel universe, the Neandertal would be studying our bones."**
> —*Edward K. Chew*
> KINGSTON, ONTARIO

Terrible Thing to Waste

One of the most important messages in Matthew L. Wald's "What Now for Nuclear Waste?" is that we really have several options for handling nuclear waste. All the options, whether aboveground storage for a couple of hundred years until we decide on the next step, reprocessing fuel to remove the long-lived isotopes to be burned in a fast reactor, or even the original plan for burying spent fuel will have little to no impact on future generations or the environment. There are no plausible scenarios for controlling climate change that do not require use of nuclear energy. Apart from hydroelectricity, it is the only base-load source that does not require burning fossil fuels. For this country, there are no new major hydro sources available. Unfortunately, as Wald notes, the process for deciding how we ultimately handle nuclear waste has been driven largely by politics and not science. It is time, however, that we mature past the disingenuous arguments about nuclear waste as a roadblock to any new nuclear plants and build the facilities we need.

William H. Miller
Nuclear Science and Engineering Institute
University of Missouri–Columbia

In a Parallel Universe . . .

It's such a shame the Neandertals had to leave us, as Kate Wong recounts in "Twilight of the Neandertals." Imagine sharing the planet with another race of stocky people like Tolkien's dwarfs! What I can't grasp is why we need to explain them away as anatomically inferior evolutionary dead ends. Maybe in some parallel universe, things went the other way. The Neandertal would be studying our bones and talking about how we were built weaker, had smaller brains, and were poorly adapted to the cold during an ice age. Of course we died out!

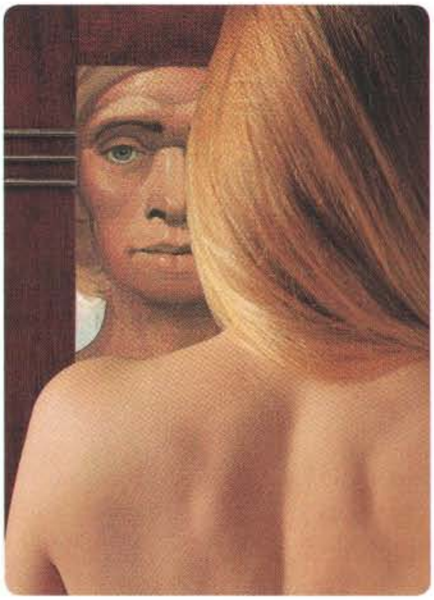
Our own history has seen plenty of civilizations go extinct while others have expanded to fill the void, and we are all built the same way. So why did we luck out over the Neandertal? Who knows? Maybe we had developed a higher level of social organization? Maybe when you get started in a more agreeable climate, you have time to experiment with higher concepts like extended tribal networks and such? We may never know what gave us an edge, but I'd rather not jump to conclusions about our mental or physical superiority.

Edward K. Chew
Kingston, Ontario

Why do your close-up illustrations of supposed Neandertals show them as overweight, aging, puffy-skinned, sparsely bearded guys with bad hairstyles? Where is the archaeological evidence for any of these traits in representative Neandertals? Okay, they may have had heavy browridges and big ears, but so did Clark Gable, so why not use him as your model? The Neandertal guys were probably very proud of their neatly trimmed pencil moustaches—consistent with the real evidence for

bone tools, blades and decorated bodies.

Peter Brooker
West Wickham, England



CROATIAN NATURAL HISTORY MUSEUM

THE EDITORS REPLY: *Wong's "Who Were the Neandertals?" (April 2000) featured an attractive female Neandertal gazing into a mirror* (above).

Laissez-Faire?

The ongoing debate on genetically modified crops, as espoused in "A Seedy Practice" [Scientific American Perspectives], is not about stopping public relations efforts by these companies. Companies market products, and there is nothing inherently wrong with that. Nor is it about whether I or anyone else thinks genetically modified foods are good or bad. The problem is that today these claims are mostly opinion, because independent research is not available to properly inform discussions.

The debate needs to be about how our regulatory structure has sold out to industry, which is represented by a highly concentrated, centralized power structure that controls our conventional food system. It needs to be about holding the food system and our government accountable. Most important, it needs to demand that companies and the government do what is right, just and fair.

"Jambutter"
via ScientificAmerican.com

"A Seedy Practice" criticized the limitations to research on commercial, patent-protected seed products. While considerable research is currently being conducted on these products, 27 individuals from the research community and the seed industry who convened this past June in Ames, Iowa, achieved significant progress and alignment. The seed industry committed itself to a set of principles that continue and strengthen the support for public-sector research on commercially available, patent-protected seed products. The principles were approved by the American Seed Trade Association and by the Biotechnology Industry Organization in September, and a final version will be publicly available in December.

Andrew W. LaVigne
President and CEO
American Seed Trade Association

It's No Life

I'm glad to see malaria addressed in your magazine, as Jeffrey D. Sachs does in "Good News on Malaria Control" [Sustainable Developments]. The problem I have with celebrating good results from mass distribution of insecticide-treated bed nets is that it encourages the world to turn to other more pressing health threats.

I live near the equator in West Africa, and mosquitoes generally become active as it is getting dark between 6:30 and 7:00 P.M. To suggest that everyone should run off to bed at that time is incompatible with the normal quality of life. Separation of people from the mosquito by using nets is only a temporary solution. The mosquito itself needs to be dealt with.

Jacqueline Leigh
Freetown, Sierra Leone

ERRATA In "Really Long-Term Memory" [Updates], we wrote that a carbon nanotube–based memory device had been described in the June 10 *Nano Letters.* The research appeared instead in the May 13 issue of that journal.

In "Hypersphere Exotica" [News Scan], Davide Castelvecchi wrote about possible nonstandard spheres having $2^k - 2$ dimensions, including the cases 254, 510 and 1,026. The last number should have been 1,022.

In "Good News on Malaria Control" [Sustainable Developments], Jeffrey D. Sachs wrote that the cost of mosquito nets is \$0.50 per child per year. The actual cost is \$1 per child per year.

SCIENTIFIC AMERICAN®
Established 1845

How to Contact Us

SUBSCRIPTIONS
For new subscriptions, renewals, gifts, payments, and changes of address: U.S. and Canada, 800-333-1199; outside North America, 515-248-7684 or www.ScientificAmerican.com

REPRINTS
To order reprints of articles: Reprint Department, Scientific American, 75 Varick Street, 9th Floor, New York, NY 10013-1917; 212-451-8877, fax: 212-355-0408; reprints@SciAm.com

PERMISSIONS
For permission to copy or reuse material: Permissions Department, Scientific American, 75 Varick Street, 9th Floor, New York, NY 10013-1917; 212-451-8877; www.ScientificAmerican.com/permissions or 212-451-8546 for procedures. Please allow three to six weeks for processing.

ADVERTISING
www.ScientificAmerican.com has electronic contact information for sales representatives of Scientific American in all regions of the U.S. and in other countries.

Fuzzy Moon • Incandescent Fraud • Whales for Oil

Compiled by Daniel C. Schlenoff

DECEMBER 1959

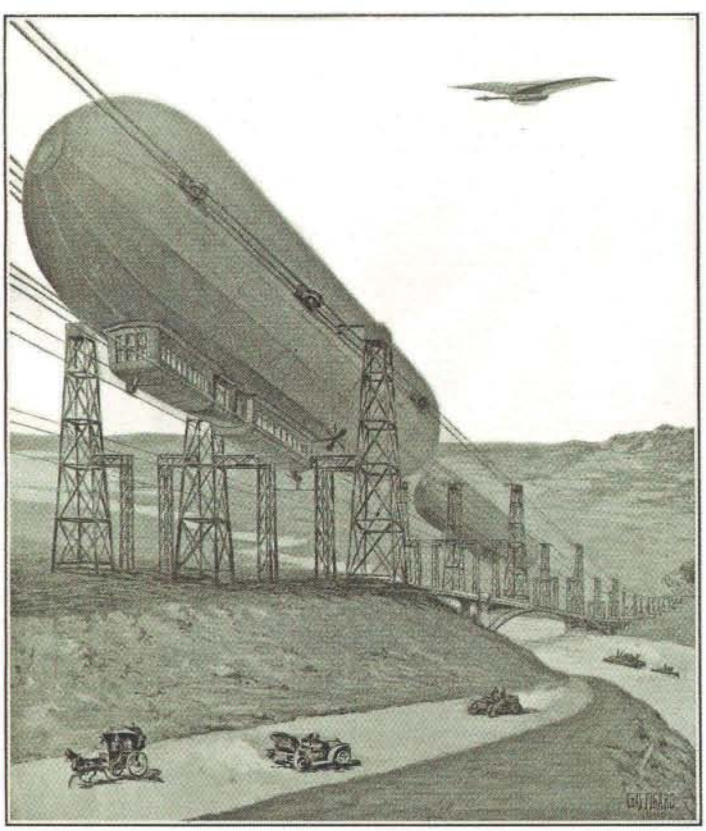
THE FAR SIDE—"Man's first blurred view of the other side of the moon suggests that current theories of the origin and history of our natural satellite may require revision. The Soviet vehicle, launched on October 3, crossed the moon's orbit some three days later. Shortly thereafter, in response to radio signals from earth, it pointed its two cameras at the moon and made the photographs. They were developed in the vehicle and were radioed back to the earth. One of them was released in Moscow on October 27. It revealed a number of sizable craters as well as a mountain range of peculiar topography (Soviet workers have christened it the Soviet Mountains)."

[NOTE: The "mountains" later turned out to be rays of material ejected from craters and were quite flat.]

BODY FAT—"For many writers, overeating is identified with weight gain, and no attempt is made to explain the processes involved. If obesity is to be understood, these processes must be recognized. Recent studies have shown that fat tissue is more than a storage depot for excess food. It lives and participates actively in the metabolism of the body. It converts a substantial part of dietary sugar and starch to fat even when a person is at constant weight. It throttles the flow of energy in the body by adjusting the outflow of fatty acids to the needs of working cells. It responds to hormones, which integrate its performance into the coordinated working of the body. Since all of these processes in fat tissue are affected by obesity, a theory of the disease that is based entirely on overeating seems inadequate. —Vincent P. Dole"

DECEMBER 1909

FLYING RAILWAY—"A German engineer has conceived a novel and marvelously impracticable mode of transit, a sort of cross between the airship and the electric railway, in which a balloon supports the weight of passenger cars, which run on aerial cables and are propelled by electricity [*see illustration*]. The balloon is of the rigid Zeppelin type of construction, and is propelled by electric motors capable of developing an airspeed of about 125 miles per hour. There are engineering as well as financial objections to this scheme."



ZEPPELIN RAILWAY—Melding technologies of rail and dirigible, 1909

BULB SWINDLE—"English technical journals have been warning purchasers of incandescent electric lamps against swindlers who install lamps which purport to contain metallic filaments but which soon prove to be very short-lived carbon filament lamps. The lamps, when first installed, give off a brilliant light and appear to be very economical, as tested with the agent's ampere meter, but the bulbs soon become blackened, the luminosity diminishes, and in a short time the lamps break. Bulbs of ground glass are employed, so that the purchaser cannot see the alleged metallic filaments."

DECEMBER 1859

WHALE OIL—"In 1820 the number of ships in England and Scotland engaged in the whale fisheries of the Arctic seas was 156, and the amount of oil obtained yearly was 18,725 tuns. Owing to the increased difficulty of catching whales, and the rapid extension of lighting streets and factories with gas, the whaling business was afterwards almost extinguished. The old vessels were sold for carrying coal, and an immense amount of property was sacrificed. Within the last few years, however, the business seems to be growing up again, even though vast quantities of coal oil are now made and sold. It is believed that the whale oil, especially sperm, is still superior to all other unguents for the lubrication of machinery; hence, as vast quantities are required for railroads and other purposes, there is much to incite persons to engage in the whale fishing."

SCIENTIFIC AMERICAN, VOL. CI, NO. 23; DECEMBER 4, 1909

Research & Discovery

Splitting Time from Space

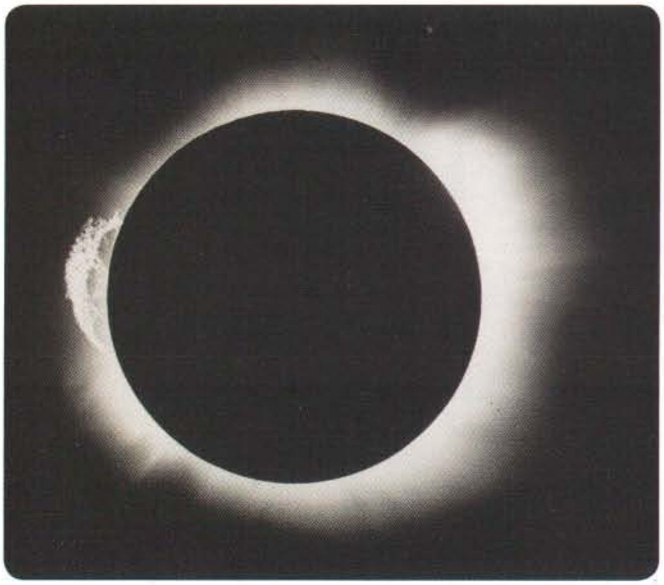
Buzz about quantum gravity that topples Einstein's spacetime BY ZEEYA MERALI

WAS NEWTON RIGHT AND EINSTEIN WRONG? IT SEEMS THAT unzipping the fabric of spacetime and harking back to 19th-century notions of time could lead to a theory of quantum gravity.

Physicists have struggled to marry quantum mechanics with gravity for decades. In contrast, the other forces of nature have obediently fallen into line. For instance, the electromagnetic force can be described quantum-mechanically by the motion of photons. Try and work out the gravitational force between two objects in terms of a quantum graviton, however, and you quickly run into trouble—the answer to every calculation is infinity. But now Petr Hořava, a physicist at the University of California, Berkeley, thinks he understands the problem. It's all, he says, a matter of time.

More specifically, the problem is the way that time is tied up with space in Einstein's theory of gravity: general relativity. Einstein famously overturned the Newtonian notion that time is absolute—steadily ticking away in the background. Instead he argued that time is another dimension, woven together with space to form a malleable fabric that is distorted by matter. The snag is that in quantum mechanics, time retains its Newtonian aloofness, providing the stage against which matter dances but never being affected by its presence. These two conceptions of time don't gel.

The solution, Hořava says, is to snip threads that bind time to space at very high energies, such as those found in the early universe where quantum gravity rules. "I'm going back to Newton's idea that time and space are not equivalent," Hořava says. At low energies, general relativity emerges from this underlying framework, and the fabric of spacetime restitches, he explains.



ECLIPSING EINSTEIN? A solar eclipse confirmed gravitational lensing and Einstein's concept of spacetime. But a new quantum gravity theory now generating excitement separates time and space.

Hořava likens this emergence to the way some exotic substances change phase. For instance, at low temperatures liquid helium's properties change dramatically, becoming a "superfluid" that can overcome friction. In fact, he has co-opted the mathematics of exotic phase transitions to build his theory of gravity. So far it seems to be working: the infinities that plague other theories of quantum gravity have been tamed, and the theory spits out a well-behaved graviton. It also seems to match with computer simulations of quantum gravity.

Hořava's theory has been generating excitement since he proposed it in January, and physicists met to discuss it at a meeting in November at the Perimeter Institute for Theoretical Physics in Waterloo, Ontario. In particular, physicists have been checking if the model correctly describes the universe we see today. General relativity scored a knockout blow when Einstein predicted the motion of Mercury to greater accuracy than Newton's theory of gravity could.

Can Hořava gravity claim the same success? The first tentative answers coming in say "yes." Francisco Lobo, now at the University of Lisbon, and his colleagues have found a good match with the movement of planets.

Others have made even bolder claims for Hořava gravity, especially when it comes to explaining cosmic conundrums such as the singularity of the big bang, where the laws of physics break down. If Hořava gravity is true, argues cosmologist Robert Brandenberger of McGill University in a paper published in the August *Physical Review D*, then the universe didn't bang—it bounced. "A universe filled with matter will contract down to a small—but finite—size and then bounce out again, giving us the expanding cosmos we see today," he says. Brandenberger's calculations show that ripples produced by the bounce match those already detected by satellites measuring the cosmic microwave background, and he is now looking for signatures that could distinguish the bounce from the big bang scenario.

Hořava gravity may also create the "illusion of dark matter," says cosmologist Shinji Mukohyama of Tokyo University. In the September *Physical Review D*, he explains that, in certain circumstances, Hořava's graviton fluctuates as it interacts with normal matter, making gravity pull a bit more strongly than expected in general relativity. The effect could make galaxies appear to contain more matter than can be seen. If that's not

PHOTO RESEARCHERS, INC.

enough, cosmologist Mu-In Park of Chonbuk National University in South Korea believes that Hořava gravity may also be behind the accelerated expansion of the universe, currently attributed to a mysterious dark energy. One of the leading explanations for its origin is that empty space contains some intrinsic energy that pushes the universe outward. This intrinsic energy cannot be accounted for by general relativity but pops naturally out of the equations of Hořava gravity, Park says.

Hořava's theory, however, is far from perfect. Diego Blas, a quantum gravity researcher at the Swiss Federal Institute of Technology (EPFL) in Lausanne has found a "hidden sickness" in the theory when double-checking calculations for the solar system. Most physicists examined ideal cases, assuming, for instance, that Earth and the sun are spheres, Blas explains: "We checked the more realistic case, where the sun is almost a sphere, but not quite." General relativity pretty much gives the same answer in both the scenarios. But in Hořava gravity, the realistic case gives a wildly different result.

Along with Sergei M. Sibiryakov, also at EPFL, and Oriol Pujolas of CERN near Geneva, Blas has reformulated Hořava gravity to bring it back into line with general relativity. Sibiryakov presented the group's model in September at a meeting in Talloires, France.

Hořava welcomes the modifications. "When I proposed this, I didn't claim I had the final theory," he says. "I want other people to examine it and improve it."

Gia Dvali, a quantum gravity expert at CERN, remains cautious. A few years ago he tried a similar trick, breaking apart space and time in an attempt to explain dark energy. But he abandoned his model because it allowed information to be communicated faster than the speed of light.

"My intuition is that any such models will have unwanted side effects," Dvali thinks. "But if they find a version that doesn't, then that theory must be taken very seriously."

Zeeya Merali is based in London.

Extreme Monotremes

How egg-laying mammals survived their live-birthing competitors

BY CHARLES Q. CHOI

ONLY TWO KINDS OF EGG-LAYING MAMMALS are left on the planet today—the duck-billed platypus and the echidna, or spiny anteater. These odd "monotremes" once dominated Australia, until their pouch-bearing cousins, the marsupials, invaded the land down under 71 million to 54 million years ago and swept them away. New research suggests these two kinds of creatures managed to survive because their ancestors took to the water.

NICOLE DUPLAIX Getty Images

DUCK-BILLED PLATYPUS and the other egg-laying mammal, the echidna, may owe their existence to their ancestors adapting to life in water, thereby avoiding marsupial competition.

Before making their way to Australia, the marsupials had migrated from Asia to the Americas to Antarctica. Forced to contend with all the animals along the way, marsupials may have been primed for competition, hence accounting for their overwhelming success in Australia, says evolutionary biologist Matthew Phillips of the Australian National University in Canberra: "The question then becomes, 'Why did the monotremes survive?'"

Phillips and his colleagues suggest that platypuses and echidnas made it through the marsupial invasion because their ancestors sought refuge where marsupials could not follow—the water. When marsupials are born, they need to constantly suckle milk for weeks, and as such, newborns could drown if their mothers ever had to swim for long.

The theory seems plausible for platypuses, which are amphibious creatures. Echidnas, however, dwell solely on land. The investigators used genetics to come up with an answer. They found that echidnas diverged from platypuses only 19 million to 48 million years ago, meaning that echidnas recently had semiaquatic ancestors and only later recolonized the land. A number of features of echidnas indicate that they may have once had an amphibious platypuslike forerunner—streamlined bodies, rearward-projecting hind limbs that could serve as rudders, and the contours of a ducklike bill during embryonic development.

A previous study of early monotreme fossils had suggested the platypus and the echidna diverged more than 110 million years ago, far longer than the genetic analysis indicates. But Phillips's team reanalyzed 439 features of those early fossils and found that echidnas and recently evolved platypuses were better grouped together instead of with more ancient fossils. The reconstructed lineages support the researchers' genetic findings, which they reported online September 23 in the *Proceedings of the National Academy of Sciences USA*. "The genes and the bones now appear to be telling the same story, which is encouraging," says mammalogist Robin Beck of the American Museum of Natural History in New York City, who did not take part in this research.

So far scientists have found no fossil

evidence of an echidna transition from water; the fossil record of monotremes remains quite incomplete, Beck says. But a number of fossil sites in Australia are 20 million to 25 million years old, about when the researchers think echidnas evolved. "With luck, future expeditions to these sites will discover fossil echidnas that document a transition from a platypuslike form," he suggests.

The presence in monotremes of egg laying and other primitive traits from distant ancestors, such as reptilelike shoulders, is often offered as reasons for their apparent inferiority, Phillips says. These new findings help to recast these archaic features in a positive light—for instance, whereas the reptilelike shoulders are poor for running fast, they provide strong bracing, allowing for huge shoulder and arm musculature to help echidnas dig into the dirt and platypuses maneuver in the water. "Most reptiles also possess these 'primitive' traits and yet, in terms of species numbers, are more successful than any mammal group," Phillips adds.

Charles Q. Choi is a frequent contributor based in New York City.

Tinier Tyrannosaurs

Dainty relatives of *T. rex* force an evolutionary rethinking BY KATE WONG

LOOMING LARGER THAN A DOUBLE-DECKER bus and baring teeth that have been likened to serrated bananas, *Tyrannosaurus rex* has long been considered one of the most fearsome creatures ever to have walked the earth. Other familiar tyrannosaurs, such as *Albertosaurus* and *Tarbosaurus*, were likewise terrifying in their size and bite—despite those absurd-looking but characteristic arms. But it turns out that not all tyrannosaurs have these hallmark features.

This past fall paleontologists unveiled two tyrannosaurs new to science that are shaking up long-standing ideas about everyone's favorite mega-predator. The finds are forcing researchers to reevaluate the origin of the tyrannosaur body plan and reconsider what they thought they knew about the diversity of this well-studied group. "Our view of tyrannosaur evolution has changed dramatically," says doctoral student Stephen L. Brusatte of the American Museum of Natural History in New York City.

Over the past decade researchers have established that behemoth tyrannosaurs such as *T. rex* evolved from smaller ancestors. And they thought that the signature features of *T. rex*—including a huge skull built for tearing into flesh and bone, puny arms, and running legs and feet—were inextricably linked to the evolution of large body size. But in the October 16 *Science*, Paul C. Sereno of the University of Chicago and his colleagues, including Brusatte, described a new tyrannosaur, *Raptorex kriegsteini*, that upends this idea.

MINI ME: *T. rex* dwarfs the newly described *Raptorex*, a pint-size tyrannosaur from Inner Mongolia that had many of the hallmarks of its larger successors.

COURTESY OF PAUL C. SERENO *University of Chicago*

Unearthed in Inner Mongolia, *Raptorex* lived 125 million years ago—60 million years before *T. rex* terrorized North America. The fossil shows that, in fact, the *T. rex* body design debuted in a dainty dino, one that weighed little more than a human and was about 1/100th the size of *T. rex*. As such, *Raptorex* clears up some puzzling aspects of *T. rex* anatomy, observes Thomas R. Holtz, Jr., of the University of Maryland, a tyrannosaur authority who was not involved in the research. For example, paleontologists have long wondered why *T. rex* had lower limbs engineered for speed when the animal's sheer heft would have precluded swift locomotion. But the presence of fleet legs and feet in the much older *Raptorex* indicates that *T. rex*'s lower limb architecture is just an evolutionary holdover from a smaller, faster ancestor.

The fact that the *Raptorex* body plan was simply scaled up in later tyrannosaurs such as *T. rex* attests to the adaptive value of those trademark traits. But not all members of this group went that evolutionary route, as Brusatte and his colleagues revealed in a paper published in the October 13 *Proceedings of the National Academy of Sciences USA* that describes the second new tyrannosaur.

Discovered in 2001 on an expedition in Mongolia's Gobi Desert, the 65-million-year-old specimen, named *Alioramus altai*, has a suite of features that deviate sharply from the tyrannosaur norm. Tipping the scales at an estimated 350 kilograms, this dinosaur—believed to have been about nine years old when it died—is larger than *Raptorex* but still only half the size of a nine-year-old *T. rex* (which reached full size in 18 years). Furthermore, it has a "totally weird skull shape," Brusatte asserts. Among other bizarre traits, the skull is long and slender, somewhat like a crocodile's, and it lacks the banana-shaped teeth and enlarged browridges that enabled *T. rex* and other tyrannosaurs to bite with bone-crushing force.

The skull of *A. altai* also exhibits eight small horns, including one on each cheek that stuck out to the side. Though modest compared with the horns of dinosaurs like *Triceratops*, the horns of *Alioramus* are quite extravagant for a tyrannosaur. They would not have done much good in combat, so Brusatte surmises that they served to attract mates once the animal reached sexual maturity.

A. altai might seem wimpy, but its more

delicate features may have been the key to surviving alongside its bigger, badder brother, *Tarbosaurus*. "Different skull shapes and different bodies probably allowed *Alioramus* and *Tarbosaurus* to coexist" much as lions and cheetahs share the African grasslands today, Brusatte comments. Whereas *Tarbosaurus* probably pursued large animals using brute force, *Alioramus* could have snagged smaller animals using the speed and stealth that its smaller proportions allowed. In the lush forests of Late Cretaceous Mongolia, *Alioramus* would have had plenty of manageable prey to choose from, including numerous species of small dinosaurs.

The new *A. altai* fossil resolves an enduring mystery about a genus that scientists previously knew from a single fragmentary and poorly described specimen, named *Alioramus remotus*. Based on the earlier find, researchers had debated whether *Alioramus* was a primitive tyrannosaur ancestor or a more derived creature possibly related to *T. rex*. Some investigators even wondered whether it was a distinct genus at all, suggesting that the creature could just be a juvenile *Tarbosaurus*. But analysis of the new specimen, which is much more complete, reveals a creature that is very closely related to *T. rex*, despite lacking the hallmark tyrannosaur traits.

Questions remain about *Alioramus*, however. Holtz notes that researchers will need to find an adult *Alioramus* to assess to what extent the animal's unusual features are the result of having a slower growth rate than larger tyrannosaurs versus simply stopping growth earlier.

COURTESY OF J. H. MATTERNES

Ardi Unveiled

Fifteen years in the making, a dossier of papers on the 4.4-million-year-old early human *Ardipithecus ramidus* ("Ardi," as the most complete female specimen is known) were published in the October 2 *Science*. The long-awaited research on the hominid, pieced together from many different individuals, paints a clearer picture of what the last common ancestor of humans and chimpanzees may have looked like. Details on the research and a slide show appear on the *Scientific American* Web site: **www.ScientificAmerican.com/dec2009**

Medicine & Health

Inflammatory Clues

Not just obesity—more evidence links inflammation with diabetes

BY MELINDA WENNER

NEARLY 21 MILLION AMERICANS SUFFER from type 2 diabetes, and every year 800,000 more are diagnosed. Considering the growing numbers, scientists are trying to fit together the disease's disparate puzzle pieces. People who acquire it are typically obese, suffer from chronic inflammation and are resistant to insulin, the hormone that removes sugar from the blood and stores it as energy. For years no one has known exactly how the three characteristics are related, if at all. But a handful of recent studies suggest that they are inextricably linked through the actions of specific inflammatory immune cells and a master genetic switch—and the hope is that an understanding of the relations could open the door to new therapeutic opportunities.

Several decades ago scientists noticed that people with type 2 diabetes have overly active immune responses, leaving their bodies rife with inflammatory chemicals. In the early 1990s researchers at Harvard University pinpointed one major immune player as TNF-alpha, a chemical secreted by immune cells; such compounds are generally referred to as cytokines. They found high levels of the cytokine in the fat tissue of rats with type 2 diabetes, and when they bred obese rats that could not make the cytokine, diabetes did not develop in the animals. Researchers have since shown that TNF-alpha—and, more generally, inflammation—activates and increases the expression of several proteins that suppress insulin-signaling pathways, making the human body less responsive to insulin and increasing the risk for insulin resistance.

So what causes the inflammation? Although type 2 diabetes can develop in patients of normal weight, most scientists agree that "obesity is the driving force," says Jerrold Olefsky, an endocrinologist at the University of California, San Diego. After fat cells have expanded as a result of weight gain, they sometimes do not get enough oxygen from the blood and start to die, he explains. The cellular death recruits immune cells to the scene.

Insulin resistance causes inflammation, too. In a study published in the August online version of *Diabetes*, H. Henry Dong and his colleagues at the University of Pittsburgh showed that a protein called FOXO1 serves as a master switch that turns on the expression of another key inflammatory cytokine, interleukin 1-beta, which also interferes with insulin signaling. Normally insulin keeps FOXO1 in check; it "rapidly inhibits FOXO1" by moving it out of the nucleus so it can be targeted for degradation, Dong says. But when a person becomes insulin-resistant and pancreatic cells no longer produce enough insulin to overcome the resistance, activity of FOXO1 increases.

Dong's results suggest that inflammation and insulin resistance reinforce each other via a positive feedback loop. And indeed, the two often come together: for instance, rheumatoid arthritis, an inflammatory disease, heightens the risk of insulin resistance developing, Dong states.

The findings could lead to the development of new therapeutics. Dong says that "we are trying to create an antagonist, a

molecule, to inhibit FOXO1 activity" enough to end diabetes but not so much as to impair FOXO1's other roles in the body, which include aiding muscle cell growth.

Other scientists are targeting the immune cells that release cytokines. In 2003 researchers at Columbia University and at Millennium Pharmaceuticals discovered hoards of macrophages, immune cells whose primary role is to engulf pathogens, in the fat stores of people with type 2 diabetes. Olefsky and his colleagues later genetically engineered mice that could not produce these macrophages and showed that "the animals were protected from obesity-induced insulin resistance," even if they were fat, he says. "That throws out the idea that if you could find a less noxious way in humans of inhibiting that macrophage inflammatory program, you could have a therapeutic." The key would be to ensure that such a drug did not interfere with essential immune system activity, Olefsky notes.

Perhaps the biggest remaining question is whether inflammation always precedes insulin resistance. "We don't truly know which comes first," says Aruna Pradhan, an epidemiologist at Brigham and Women's Hospital in Boston. Insulin resistance could develop first and then incite inflammation through its effects on FOXO1. "It's a chicken-and-egg question," Dong says. "Nobody knows."

And inflammation and insulin resistance aren't the only factors to consider: genetics and environmental influences such as nutrition play a role in diabetes, too. In September 2009 Pradhan and her colleagues published a surprising study in the *Journal of the American Medical Association* showing that drugs that reduced insulin resistance had little effect on inflammation levels. Bizarrely, the subjects who received placebos had fewer signs of inflammation at the end of the study than those taking the drugs did, suggesting a complex interplay of factors. So even as scientists create a clearer picture of inflammation and diabetes, new puzzle pieces seem to keep adding more complexity to a complex disease.

Melinda Wenner described how the architecture of the cell nucleus affects health in the October issue.

Conditional Consciousness

Patients in vegetative states can form new memories BY KATHERINE HARMON

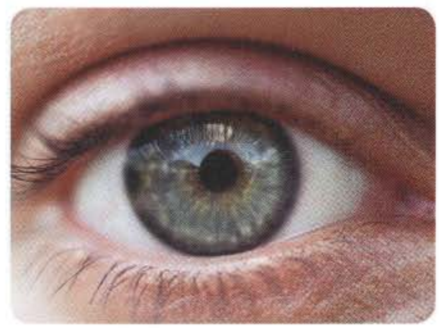
IN PATIENTS WHO HAVE SURVIVED SEVERE brain damage, judging the level of actual awareness has proved a difficult process. And the prognosis can sometimes mean the difference between life and death. New research suggests that some vegetative patients are capable of simple learning—a sign of consciousness in many who had failed other traditional cognitive tests.

To determine whether patients are in a minimally conscious state (in which there is some evidence of perception or intentional movement) or have sunk into a vegetative state (in which neither exists), doctors have traditionally used a battery of tests and observations. Many of them require some subjective interpretation, such as deciding whether a patient's movements are purposeful or just random. "We want to have an objective way of knowing whether the other person has consciousness or not," says Mariano Sigman, who directs the Integrative Neuroscience Laboratory at the University of Buenos Aires.

That desire stems in part from surprising neuroimaging work that showed that some vegetative patients, when asked to imagine performing physical tasks such as playing tennis, still had activity in premotor areas of their brains. In others, verbal cues sparked language sectors. A recent study found that about 40 percent of vegetative state diagnoses are incorrect.

To explore possible tests of consciousness in patients, Sigman and his colleagues turned to classical conditioning: they sounded a tone and then sent a light puff of air to the patient's eye. The air puff would cause a patient to blink or flinch the eye, but after repeated trials over half an hour, many patients would begin to anticipate the puff, blinking an eye after only hearing the tone.

If two stimuli are delivered at exactly the same time, even snails will equate the stimuli. But the team actually delayed the puff after the tone by 500 milliseconds. To associate two stimuli separated by that time gap, "you need conscious processing," says lead study author Tristan Bekinschtein of the Impaired Consciousness Research Group at the University of Cambridge. In fact, delaying the second stimulus by more than 200 milliseconds is enough to demonstrate some learning, he adds. By comparison, people under general anesthesia, considered to be entirely lacking awareness, showed no sign of such learning when given the tone and air-puff test.



RESPONSIVE OR NOT? A study of learning in brain-damaged patients raises questions about diagnoses of vegetative states.

NISIAN HUGHES *Getty Images*

The detection of learning, described in the September 20 *Nature Neuroscience* (*Scientific American* is part of the Nature Publishing Group), also opens up questions about when patients should be classified as being in a persistent vegetative state, in which emergence isn't predicted to be likely. (Terri Schiavo, the center of a heated national debate in 2005, was determined to be in such a state.) Decisions to end life support often depend on predic-

tions of recovery and assessments of consciousness. If "someone shows the patients can learn," Bekinschtein says, "I think it would be a very clear argument."

Indeed, the researchers found that learning ability accurately predicted the extent of recovery within the next year about 86 percent of the time. The neural reorganization that bypasses damaged parts of the brain "implies that there's room for at least some recovery," Bekinschtein notes.

The findings do not surprise everyone. Research using functional MRI on vegetative patients had already led John Whyte, principal investigator at the Neuro-Cognitive Rehabilitation Research Network at Thomas Jefferson University in Philadelphia, to question the designation system. It may be that "there is a firm line" between vegetative and minimally conscious patients," he observes. "But our tools are too crude to tell us who is on which side of the line." Or it may be that categories of consciousness are not so easy to define.

The learning tests probably could not completely supplant fMRI. Joy Hirsch, a neuroscientist at Columbia University, says that "functional imaging is by far the tool of choice" in determining consciousness because it can reveal "cognitive processes that are latent in these patients that aren't visible through [traditional] bedside tests." But neuroimaging can be expensive and hard to come by in many places, note Bekinschtein, Sigman and their study collaborators. Much of the testing was completed in Argentina, where imaging capabilities can be less available than in the U.S. or U.K. For this test, "you just need two wires, and it costs $100," Sigman states. "In practical terms, it has strong implications."

SCI AM

Read More ...

For more details, see the online version of this story at **www.ScientificAmerican.com/dec2009**

Technology

Piercing the Plasma

Beating the communications blackout of reentry and Mach 10

BY MARK WOLVERTON

THE FRUSTRATING COMMUNICATIONS BLACKOUT THAT CAN occur when a spacecraft reenters the atmosphere caused some tense moments in the earlier years of the space age—perhaps most memorably during the crippled *Apollo 13* mission. But the phenomenon could also affect communications with new aircraft and weapons systems being contemplated now by the U.S. Air Force, which hopes to find ways to pierce the blackout.

The problem arises when a speeding vehicle heats the air in front of it, ionizing it into plasma that blocks radio transmissions. It resembles the shock waves created when an airplane hits Mach 1 and breaks the sound barrier. In the case of reentering spacecraft and hypersonic aircraft, the plasma-shock boundaries form at speeds of about Mach 10. The space shuttle avoids the blackout because the craft's broad underside leaves an open area in the plasma plume trailing behind, enabling communications and telemetry data to be relayed to Earth through a network of satellites. But smaller craft are completely engulfed by the plasma.

That has concerned the air force, which plans to develop flight systems, perhaps including hypersonic missiles, surveillance craft and even manned craft that could top Mach 10. "Our standard paradigm [in the test and evaluation world] is we have a vehicle in the air and people on the ground and there's a telemetry stream of data coming down so people can monitor the vehicle," explains researcher Charles H. Jones of the Edwards Flight Test Center. Besides severing contact between the test craft and the ground, a plasma blackout also blocks the self-destruct signal that is sometimes necessary when a test vehicle strays off course.

Another crucial concern involves satellite navigation signals. "The military's becoming ever more dependent on GPS systems," notes Mark Lewis, a University of Maryland aerospace engineer and former air force chief scientist. Jones agrees, writing in the final report of a 2006 conference in Boston sponsored by the Air Force Office of Scientific Research (AFOSR) on the blackout problem: "Reception of GPS is the most critical capability for which we need to find a solution.... GPS is also the most difficult problem due to its innately weak signal."

Jones has been something of a voice in the wilderness on the problem. "Mach 10 designs aren't that common" just yet, he notes, and so "for a lot of people it's not a pressing issue." But as new higher-speed concepts in what he calls the "plasmasonic" Mach 10 realm begin to appear, the phenomenon is attracting more attention.

The 2006 conference revealed no lack of possible solutions. Ideas include designing the configuration of the craft so as to minimize the resulting plasmasonic sheath; building an "air spike" at the front of the leading edge that would protrude outside the plasma; finding frequency bands that might not be affected by the ionization; simply bullying through it with an enormously powerful transmitter; and using electrophilic injection, which means dispersing a deionizing substance, most likely water, into the plasma sheath to disrupt it. More exotic ideas involve employing high-powered lasers or ejecting a series of tiny relay devices, akin to messages in a bottle.

Although all the proposed solutions are theoretically feasible, Lewis notes that "the question then is, Are they practical from an engineering standpoint?" The water-injection idea, for example, was actually attempted back in the 1960s, during the Gem-

ini program. But an operational version would require carrying far too much water to be practical.

A variation of electrophilic injection might be a strong contender, however, using a heat shield made of an ablative material that vaporizes parts of itself and deionizes the plasma. "In terms of an engineering solution, that seems like the simplest," Jones says. Meanwhile Lewis considers himself "a stone agnostic. We've got a number of avenues to explore, and I think we're still at the point where all those avenues should be on the table." Jones has noted that a combination of techniques most likely will be required to meet all anticipated applications.

So far, Jones states, the only true consensus is that "we don't have enough experimental data to validate any of the models." Funding to study what many consider a long-range problem has been hard to come by. Although computational fluid dynamics and wind-tunnel experimentation can provide vital clues, practical solutions probably demand actual flight testing, which is expensive.

HOT STUFF COMING THROUGH: Computer modeling by Krishnendu Sinha of the Indian Institute of Technology Bombay shows the heat flow a space capsule might generate during reentry. Hottest regions exceed 6,000 degrees Celsius (*white, purple* and *red*), coolest regions a few hundred (*blue*).

KRISHNENDU SINHA *IIT Bombay*

One way or another, engineers will have to overcome the plasma blackout to usher in the high-hypersonic (or plasmasonic) world. Considering the dangers of an uncontrolled vehicle traveling at more than 10,000 miles per hour, Jones isn't kidding when he says, "I don't want a Mach 15 autonomous vehicle, possibly armed, that I can't communicate with."

Mark Wolverton is a freelance writer based in Bryn Mawr, Pa.

The Shape of Atoms

New technique images electron orbitals of individual atoms

BY DAVIDE CASTELVECCHI

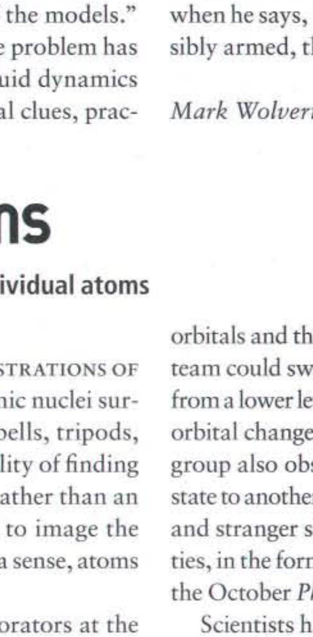
CHEMISTRY TEXTBOOKS TYPICALLY INCLUDE ILLUSTRATIONS OF atoms, but with caveats. The drawings depict atomic nuclei surrounded by electron orbitals—fuzzy spheres, barbells, tripods, and so on—but those figures represent the probability of finding an electron at a certain place around the nucleus rather than an actual "shape." Researchers have now managed to image the electron orbitals and show for the first time that, in a sense, atoms really look like those textbook images.

Specifically, Igor Mikhailovskij and his collaborators at the Kharkov Institute of Physics and Technology in Ukraine have imaged the shapes of those orbitals in carbon atoms by improving an old imaging technique called field-emission microscopy.

The researchers fashioned a chain of carbon atoms, dangled it from a graphite tip, and then placed it in front of a detection screen. When they applied an electric field of thousands of volts between the graphite and the screen, electrons flowed one by one through the graphite and along the carbon chain, until the electric field pulled them off the last atom in the chain. From the places where the electrons landed on the screen, the investigators could trace back the points where they left their orbital on the last atom. The "denser" parts of the probability clouds had a higher chance of emitting an electron, and the information from many electrons combined into an image of the clouds. "We really have an image of single atoms," Mikhailovskij says.

The pictures look, well, textbook, although only the outermost orbitals appear, which shroud the inner orbitals and the nuclei. By changing the intensity of the current, the team could switch the energy of the last atom's outermost electron from a lower level to a higher level. Correspondingly, the shape of the orbital changed from spherical to barbell, as theory predicts. The group also observed electrons switching spontaneously from one state to another—for reasons that are unclear, Mikhailovskij says—and stranger shapes that may result from the presence of impurities, in the form of other atoms such as hydrogen. The results are in the October *Physical Review B*.

Scientists have imaged single atoms before, using tools such as transmission electron microscopes (which shoot electrons through an object and measure how they get deflected) or scanning tunneling microscopes (which "feel" the sample's shape with a microscopic tip). But the atoms typically appeared as little more than blobs. Field-emission microscopy, on the other hand, pulls the electrons off the very object that is being imaged. This difference, says Alex Zettl of the University of California, Berkeley, may mean a lower chance of distortions and misinterpretations of the signal. "It is like hearing the spoken word directly from the original storyteller, not from a translator or interpreter," he says.



ORBITALS of a carbon atom, as seen by a field-emission microscope.

FROM "IMAGING THE ATOMIC ORBITALS OF CARBON ATOMIC CHAINS WITH FIELD-EMISSION ELECTRON MICROSCOPY," BY I. M. MIKHAILOVSKIJ, E. V. SADANOV, T. I. MAZILOVA, V. A. KSENOFONTOV AND O. A. VELICODNAJA, IN *PHYSICAL REVIEW B*, VOL. 80, NO. 16; OCTOBER 2009

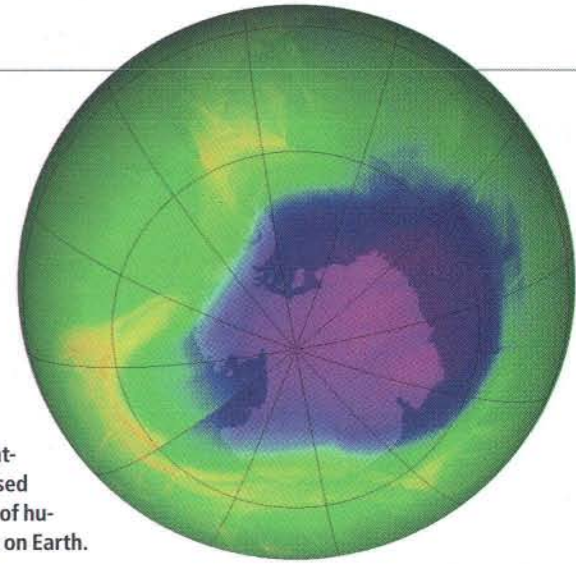
Beyond confirming textbook artwork, the technique could elucidate the properties of chains of carbon atoms, which are still largely unknown. Physicists suspect that they may be excellent conductors and mechanically strong and could become useful in future atomic-scale computers.

Energy & Environment

Setting Boundaries

Scientists propose a set of safe limits of human impacts on Earth

BY DAVID BIELLO



OZONE "HOLE" (*purple*) over Antarctica can be used as one measure of humanity's impact on Earth.

THE SCALE OF HUMANITY'S IMPACT ON THE GLOBE IS BECOMING ever more apparent: we have wiped out species at a rate to rival great extinction events of all geologic time as well as contributing to a rapidly acidifying ocean, dwindling ice caps and even sinking river deltas. Now an international group of 29 scientists has taken a preliminary stab at setting some concrete environmental thresholds for the planet.

Johan Rockström of Stockholm University and his colleagues have proposed nine "planetary boundaries" online in the September 23 *Nature*. (*Scientific American* is part of the Nature Publishing Group.) The boundaries, dealing with climate change, ocean acidification, chemical pollution and others, are meant to set thresholds, or safe limits, for natural systems with respect to human impact, although exact numbers have not yet been determined for some.

"We have reached the planetary stage of sustainability, where we are fiddling with hard-wired processes at the global Earth-system scale," Rockström says. "What are the Earth-system processes that determine the ability of the [planet] to remain in a stable state?"

The research takes as its desired stable state the Holocene epoch, the 10,000 years since the last ice age during which human civilization has flourished, and attempts to identify the key variables that might push planetary cycles past safe thresholds. So, for example, the key variable for climate change is atmospheric carbon dioxide concentration as well as its attendant rise in the amount of trapped heat. At present, atmospheric CO_2 has reached 387 parts per million (ppm), well above the preindustrial figure of 280 ppm. The estimated safe threshold identified by the scientists, including NASA climatologist James Hansen, is 350 ppm, or a total increased warming of one watt per square meter (current warming is roughly 1.5 watts per square meter).

"We begin to quantify, very roughly, where we think these thresholds might be. All have huge error bars," says ecologist Jonathan Foley, director of the University of Minnesota's Institute on the Environment and one of the authors. "We don't know exactly how many parts per million it would take to stop climate change, but we think it starts at about 350 ppm."

Humanity has already pushed past the safe threshold in two more of the nine identified boundaries—biodiversity loss and available nitrogen (thanks to modern fertilizers). And unfortunately, many of the processes affect one another as well. "Crossing one threshold makes the others more vulnerable," Foley adds. For example, biodiversity loss "on a really hot planet is accelerated."

Several scientists laud the effort but criticize the precise thresholds set. Biogeochemist William Schlesinger of the Cary Institute of Ecosystem Studies argues that the limits on phosphorus fertilizer are too lenient and can allow "pernicious, slow and diffuse degradation to persist nearly indefinitely." Allowing human water use, largely for agriculture, to expand from 2,600 cubic kilometers today to 4,000 cubic kilometers in the future will allow further degradation at such environmental disaster sites as the drying Aral Sea in Asia and seven major rivers, including the Colorado in the U.S., that no longer reach the sea, notes David Molden, deputy director general for research at the International Water Management Institute in Sri Lanka. (One cubic kilometer of water equals about 264 trillion gallons.)

Even the 350-ppm limit for carbon dioxide is "questionable," says physicist Myles Allen of the Climate Dynamics Group at the University of Oxford. Instead he thinks that focusing on keeping cumulative emissions below one trillion metric tons might make more sense—although that means humanity has already used up more than half of its overall emissions budget.

Regardless of impacts on the planet, the human condition has likely never been better in terms of material prosperity. The question is: "How do you continue to improve the human condition?" Foley asks. "How can we sustain a world that will reach nine billion people without destroying the planet? At least knowing a bit where the danger zones are is a really important first step."

There are grounds for hope. Humanity has crossed one of these thresholds before—namely, diminishing levels of stratospheric ozone caused by emissions of ozone-destroying chemicals (the "ozone hole"). We pulled back thanks to international cooperation and the 1989 Montreal Protocol. "We did manage to move ourselves away from the ozone boundary and have made serious efforts at regional levels to protect biodiversity; reduce agricultural pollution, aerosols and water demand; and slow land conversion," points out environmental scientist Diana Liverman of the University of Arizona, one of the authors of the new thresholds. "This provides some hope that we can manage our planetary impact if we choose."

Read More ...

SCI AM For a complete listing of the planetary boundaries and thresholds, see the online version of this story at **www.ScientificAmerican.com/dec2009**

NASA

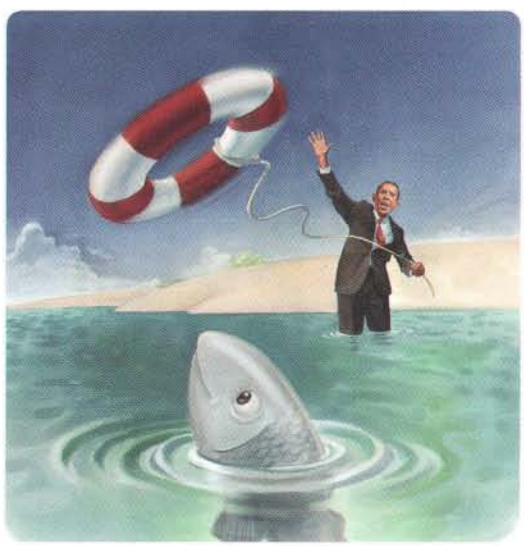
Zoning for Oceans

The time when we could do anything we want anywhere we want in the oceans is over

BY THE EDITORS

For decades the seas off U.S. shores have been roiled by controversies over where to drill for oil, how to reel in overfishing, and whom to blame for toxic streams of continental runoff. A failure to manage these problems effectively has already put the nation's oceanic realms in serious jeopardy. And now we are inviting new industries to stake their own claims on the blue frontier. To generate clean energy from wind and tides, we need permanent installations. To grow more food, we need offshore farms.

Without a plan to manage these proliferating activities, they are very likely to exacerbate the existing shambles. President Barack Obama turned a spotlight to this challenge in June, when he charged an interagency task force with detailing the country's first national ocean policy. Its official report is due out this month, but a draft hints at a bold way of reconciling our competing needs and interests, both economic and environmental: zoning U.S. waters (which extend 200 nautical miles from the coast) much the way we zone our cities and public lands [see "Ocean Overhaul," by Sarah Simpson, on page 32].



Precedent for this approach comes from a fisheries management strategy that has shown great promise in recent years, called catch shares. Unlike traditional fish quotas, which typically ignite a race among fishers to haul in the largest possible share of allowable catch, catch-share schemes allocate shares of the fisherywide quota before the season starts. Secure in the number of fish they can catch, fishers are free to plan how and when to do their work, making them more likely to prioritize practices that do not damage fish habitat and thereby maintain their ability to catch more fish in future years. In some cases, conservation advocates can buy an individuals' shares in exchange for their not fishing at all. So far the U.S. uses catch shares to manage 12 commercial fish stocks, including halibut, pollock and Atlantic cod.

Catch shares integrate the economic and environmental sides of fisheries management. Zoning would do the same on a broader scale. Currently our system of ocean governance is piecemeal. Since the early 1900s the U.S. has been coming to terms (or not) with its impact on the marine realm one problem at a time. Today some 20 different federal agencies each manage their own use, typically without regard to what the others are doing. And none looks out for the overall health of the oceans. Community and environmental groups have stepped into the breach, but their main tool is litigation—which is blunt, expensive and divisive.

The draft policy of the presidential task force recommends the creation of a National Ocean Council to coordinate the various agencies. Zoning goes further. You don't need traffic lights if there isn't much traffic, but as a frontier village becomes a bustling city, the pioneers need a comprehensive plan, and they need maps telling everyone what they can do where. Extending this "planning and zoning" paradigm offshore makes good sense. Zoning would give all parties with a stake in the seas the security of knowing certain spaces are designated for their desired uses. Commerce benefits because environmental groups are less likely to block industry on a case-by-case basis. Marine ecosystems benefit because conservation finally gets an equal seat at the planning table with the fishing and petroleum industries. A pioneering zone map set up by Australia some three decades ago helped to save the Great Barrier Reef.

To set up the zones requires good science. Evidence clearly shows that areas around estuaries, coastal wetlands, reefs and submarine mountains are among the most important to protect, whereas a sandy bottom already degraded by coastal pollution might be a good spot to authorize, say, sand and gravel mining. Creating tradable rights and subleasing options within the zoning system could give groups additional incentives to cooperate. The managers of a conservation zone could sell rights to fish in their zone in exchange for increased conservation practices in a fishing zone. Or a wind farm could sublease the rights to the aquaculture underneath its turbines.

The risk is that the zoning idea will get mired in decades-long debates while the oceans continue to deteriorate. The U.S. needs to act with urgency. As other nations do the same, they can work together to manage the high seas that are the domain of no single country. Cooperation is no longer optional; it is essential. We don't have another 100 years to get it right. ■

ILLUSTRATION BY MATT COLLINS

Transgressing Planetary Boundaries

Challenges of population control and food production need to be tackled in tandem

BY JEFFREY D. SACHS

We are eating ourselves out of house and home. Recently, in the September 24 issue of *Nature*, Johan Rockström and his colleagues proposed 10 "planetary boundaries" to define safe limits of human activity. (*Scientific American* is part of the Nature Publishing Group.) Those limits include caps on greenhouse gas emissions, biodiversity loss, the global conversion of land cover to cropland, and other mega-impacts on the earth's ecosystems. Yet humanity has already exceeded several of them and is on a trajectory to exceed most of the others. The rising demand for food plays a large role in those transgressions.

The green revolution that made grain production soar gave humanity some breathing space, but the continuing rise in population and demand for meat production is exhausting that buffer. The father of the green revolution, Norman Borlaug, who passed away in September at the age of 95, made exactly this point in 1970 when he accepted the Nobel Peace Prize: "There can be no permanent progress in the battle against hunger until the agencies that fight for increased food production and those that fight for population control unite in a common effort."

That common effort was inconsistent at best and sometimes essentially nonexistent. Since 1970 the population has risen from 3.7 billion to 6.9 billion and continues to increase by around 80 million a year. Food production per person has declined in some big regions, notably sub-Saharan Africa. In India the doubling of population has absorbed almost all of the increase in grain production.

Food production accounts for a third of all greenhouse gas emissions when one tallies those from fossil fuels used in growing, preparing and transporting food; the carbon dioxide released by clearing land for farming and pastures; the methane from rice paddies and ruminant livestock; and the nitrous oxide from fertilizer use.

Through the clearing of forestland, food production is also responsible for much of the loss of biodiversity. Chemical fertilizers cause massive depositions of nitrogen and phosphorus, which now destroy estuaries in hundreds of river systems and threaten ocean chemistry. Roughly 70 percent of worldwide water use goes to food production, which is implicated in groundwater depletion and ecologically destructive freshwater consumption from California to the Indo-Gangetic Plain to Central Asia to northern China.

The green revolution, in short, has not negated the dangerous side effects of a burgeoning human population, which are bound to increase as the population exceeds seven billion around 2012 and continues to grow as forecast toward nine billion by 2046. Meat consumption per capita is rising as well. Beef poses the biggest threat because cattle require up to 16 kilograms of feed grains for each kilogram of consumed meat, they emit large amounts of methane, and the fertilizer used to grow their feed contributes hugely to nitrogen oxides.

It is not enough to produce more food; we must also simultaneously stabilize the global population and reduce the ecological consequences of food production—a triple challenge. A rapid voluntary reduction in fertility rates in the poor countries, brought about by more access to family planning, higher child survival and education for girls, could stabilize the population at around eight billion by 2050.

Payments to poor communities to resist deforestation could save species habitats. No-till farming and other methods can preserve soils and biodiversity. More efficient fertilizer use can reduce the transport of excessive nitrogen and phosphorus. Better irrigation and seed varieties can conserve water and reduce other ecological pressures. And a diet shifted away from eating beef would conserve ecosystems while improving human health.

Those changes will require a tremendous public-private effort that is yet to be mobilized. As we remember Borlaug's great achievements, we must redouble our efforts to respond to his admonitions as well. The window of opportunity to achieve sustainable development is closing. ■

Jeffrey D. Sachs is director of the Earth Institute at Columbia University (www.earth.columbia.edu).

SCI AM An extended version of this essay is available at **www.ScientificAmerican.com/dec2009**

Political Science

Psychological research reveals how and why liberals and conservatives differ

BY MICHAEL SHERMER

Humans are, by nature, tribal and never more so than in politics. In the culture wars we all know the tribal stereotypes of what liberals think of conservatives: *Conservatives are a bunch of Hummer-driving, meat-eating, gun-toting, hard-drinking, Bible-thumping, black-and-white-thinking, fist-pounding, shoe-stomping, morally hypocritical blowhards.* And what conservatives think of liberals: *Liberals are a bunch of hybrid-driving, tofu-eating, tree-hugging, whale-saving, sandal-wearing, bottled-water-drinking, ACLU-supporting, flip-flopping, wishy-washy, namby-pamby bed wetters.*

Like many other stereotypes, each of these contains an element of truth that reflects an emphasis on different moral values. Jonathan Haidt, who is a psychologist at the University of Virginia, explains such stereotypes in terms of his Moral Foundations Theory (see www.moralfoundations.org), which he developed "to understand why morality varies so much across cultures yet still shows so many similarities and recurrent themes." Haidt proposes that the foundations of our sense of right and wrong rest within "five innate and universally available psychological systems" that might be summarized as follows:

1. *Harm/care:* Evolved mammalian attachment systems mean we can feel the pain of others, giving rise to the virtues of kindness, gentleness and nurturance.

2. *Fairness/reciprocity:* Evolved reciprocal altruism generates a sense of justice.

3. *Ingroup/loyalty:* Evolved in-group tribalism leads to patriotism.

4. *Authority/respect:* Evolved hierarchical social structures translate to respect for authority and tradition.

5. *Purity/sanctity:* Evolved emotion of disgust related to disease and contamination underlies our sense of bodily purity.

Over the years Haidt and his University of Virginia colleague Jesse Graham have surveyed the moral opinions of more than 110,000 people from dozens of countries and have found this consistent difference: self-reported liberals are high on 1 and 2 (*harm/care* and *fairness/reciprocity*) but are low on 3, 4 and 5 (*ingroup/loyalty, authority/respect* and *purity/sanctity*), whereas self-reported conservatives are roughly equal on all five dimensions, although they place slightly less emphasis on 1 and 2 than liberals do. (Take the survey yourself at www.yourmorals.org.)

Instead of viewing the left and the right as either inherently correct or wrong, a more scientific approach is to recognize that liberals and conservatives emphasize different moral values. My favorite example of these differences is dramatized in the 1992 film *A Few Good Men.* In the courtroom ending, Jack Nicholson's conservative marine Colonel Nathan R. Jessup is being cross-examined by Tom Cruise's liberal navy Lieutenant Daniel Kaffee, who is defending two marines accused of accidentally killing a fellow soldier. Kaffee thinks that Jessup ordered a "code red," an off-the-books command to rough up a disloyal marine trainee in need of discipline and that matters got tragically out of hand. Kaffee wants individual justice for his clients. Jessup wants freedom and security for the nation even at the cost of individual liberty, as he explains:

> "Son, we live in a world that has walls. And those walls have to be guarded by men with guns.... You don't want the truth because deep down, in places you don't talk about at parties, you want me on that wall. You need me on that wall. We use words like honor, code, loyalty. We use these words as the backbone to a life spent defending something. You use 'em as a punch line. I have neither the time nor the inclination to explain myself to a man who rises and sleeps under the blanket of the very freedom I provide, then questions the manner in which I provide it."

Personally, I tend more toward the liberal emphasis on individual fairness, justice and liberty, and I worry that overemphasis on group loyalty will trigger our inner xenophobias. But evolutionary psychology reveals just how deep our tribal instincts are and why good fences make good neighbors. And I know that ever since 9/11, I am especially grateful to all the brave soldiers on those walls who have allowed us to sleep under a blanket of freedom. ■

Michael Shermer is publisher of Skeptic *magazine (www.skeptic.com) and author of* The Mind of the Market.

PHOTOGRAPH BY BRAD SWONETZ; ILLUSTRATION BY MATT COLLINS

War Is Peace

In the 24/7 Internet world, people make lots of claims. Science provides a guide for to testing them

BY LAWRENCE M. KRAUSS

When I saw the statement repeated online that theoretical physicist Stephen Hawking of the University of Cambridge would be dead by now if he lived in the U.K. and had to depend on the National Health Service (he, of course, is alive and working in the U.K., where he always has), I reflected on something I had written a dozen years ago, in one of my first published commentaries:

"The increasingly blatant nature of the nonsense uttered with impunity in public discourse is chilling. Our democratic society is imperiled as much by this as any other single threat, regardless of whether the origins of the nonsense are religious fanaticism, simple ignorance or personal gain."

As I listen to the manifest nonsense that has been promulgated by the likes of right-wing fanatic radio hosts and moronic ex-governors in response to the effort to bring the U.S. into alignment with other industrial countries in providing reasonable and affordable health care for all its citizens, it seems that things have only gotten worse in the years since I first wrote those words.

English novelist George Orwell was remarkably prescient about many things, and one of the most disturbing aspects of his masterpiece *1984* involved the blatant perversion of objective reality, using constant repetition of propaganda by a militaristic government in control of all the media.

Centrally coordinated and fully effective reinvention of reality has not yet come about in the U.S. (even though a White House aide in the past administration came chillingly close when he said to a *New York Times* reporter, "We're an empire now, and when we act, we create our own reality"). I am concerned, however that something equally pernicious, at least to the free exercise of democracy, has.

The rise of a ubiquitous Internet, along with 24-hour news channels has, in some sense, had the opposite effect from what many might have hoped such free and open access to information would have had. It has instead provided free and open access, without the traditional media filters, to a barrage of disinformation. Nonsense claims had more difficulty gaining traction in the days when print journalism held sway and newspaper editors had the final word on what made its way into homes and when television news consisted of a half-hour summary of what a trained producer thought were the most essential stories of the day.

Now fabrications about "death panels" and oxymoronic claims that "government needs to keep its hands off of Medicare" flow freely on the Internet, driving thousands of zombielike protesters to Washington to argue that access to health care will undermine their fundamental freedom to have their insurance canceled if they get sick. And 24-hour news channels, desperate to provide "breaking" coverage at all hours, end up serving as public relations vehicles for any celebrity who happens to make an outrageous claim or, worse, decide that the competition for ratings requires them to be anything but "fair and balanced" in their reporting.

"Fair and balanced," however, doesn't mean putting all viewpoints, regardless of their underlying logic or validity, on an equal footing. Discerning the merits of competing claims is where the empirical basis of science should play a role. I cannot stress often enough that what science is all about is not proving things to be true but proving them to be false. What fails the test of empirical reality, as determined by observation and experiment, gets thrown out like yesterday's newspaper. One doesn't need to debate about whether the earth is flat or 6,000 years old. These claims can safely be discarded, and have been, by the scientific method.

What makes people so susceptible to nonsense in public discourse? Is it because we do such a miserable job in schools teaching what science is all about—that it is not a collection of facts or stories but a process for weeding out nonsense to get closer to the underlying beautiful reality of nature? Perhaps not. But I worry for the future of our democracy if a combination of a free press and democratically elected leaders cannot together somehow more effectively defend empirical reality against the onslaught of ideology and fanaticism. ■

Lawrence M. Krauss, a theoretical physicist, commentator and book author, is Foundation Professor and director of the Origins Initiative at Arizona State University (http://krauss.faculty.asu.edu).

PHOTOGRAPH BY JOHN BOSWELL; ILLUSTRATION BY MATT COLLINS

Portrait of a BLACK HOLE

By Avery E. Broderick and Abraham Loeb

By adapting a global network of telescopes, astronomers will soon get their first look ever at the dark silhouette of a black hole

You have probably seen the TV commercial in which a cell phone technician travels to remote places and asks on his phone, "Can you hear me now?" Imagine this technician traveling to the center of our Milky Way galaxy, wherein lurks a massive black hole, Sagittarius A* (Sgr A*), weighing as much as 4.5 million suns. As the technician approached within 10 million kilometers of the black hole, we would hear his cadence slow down and his voice deepen and fade, eventually turning to a monotone whisper with diminishing reception. If we were to look, we would see his image turn increasingly red and dim as he became frozen in time near the black hole's boundary, known as the event horizon.

The technician himself, however, would experience no slowing of time and would see nothing strange at the location of the event horizon. He would know he had crossed the horizon only when he heard us say, "No, we cannot hear you very well!" He would have no way of sharing his last impressions with us—nothing, not even light, can escape from gravity's extreme pull inside the event horizon. A minute after he crossed the horizon, the gravitational forces deep inside the hole would tear him apart.

In real life we cannot send a technician on such a journey. But astronomers have developed techniques that will soon allow them, for the first time, to produce images of a black hole's dark silhouette against a backdrop of hot glowing gas.

Wait, you say. Haven't astronomers reported lots of observations of black holes, including all sorts of pictures? That is true, but the pictures have been of gas or other material near a black hole, with the hole itself an invisible speck, or of huge outpourings of energy presumed to come from a black hole. In fact, we do not even know for sure whether black holes really exist [see "Black Stars, Not Holes," by Carlos Barceló, Stefano Liberati, Sebastiano Sonego and Matt Visser; Scientific American, October].

Astronomers have detected objects in the sky that are sufficiently massive and compact that, if Einstein's general theory of relativity is correct, they must be black holes, and it is customary to talk of them as if they were (as we do in this article). But until now we could not tell if these objects had the defining characteristic of a black hole—a horizon through which material can flow only one way. This question is not merely a matter of esoteric curiosity, because such horizons are at the heart of one of the deepest puzzles in theoretical physics. And images showing the dark silhouettes of black holes' event horizons would help us understand the extraordinary astrophysical processes taking place in their neighborhood.

Driving Questions

Event horizons are a source of fascination because they represent a fundamental inconsistency between two great triumphs of 20th-century physics: quantum mechanics and general relativity. Time reversibility is an essential fea-

MENACINGLY DARK DISK of the Milky Way galaxy's central black hole, and the hot gas caught in its gravity, could look like these computer simulations (*left*) when a network of radio telescopes begins observing next year. Interstellar gas will, however, blur the finer details (*above*).

COURTESY OF AVERY E. BRODERICK

KEY CONCEPTS

- Black holes are among the most mysterious objects in the universe. So far astronomers have observed them only indirectly, from their gravitational effects on stars and from the radiation emitted by hot gas spiraling toward them.
- Astronomers are adapting a network of radio telescopes to produce images of the supermassive black holes that lie at the center of the Milky Way and M87 galaxies.
- Better studies of black holes not only would help explain unusual phenomena produced by the holes but also could test Einstein's theory of general relativity and provide vital insights into the nature of gravity in extreme situations.

—The Editors

ture of the quantum-mechanical description of physical systems; every quantum process has an inverse process, which may be used, in principle, to recover any information that the original process may have scrambled. In contrast, general relativity—which explains gravity as arising from the curvature of space and predicts the existence of black holes—admits no inverse process to bring back something that has fallen into a black hole. The need to resolve this inconsistency between quantum mechanics and gravitation has been one of string theorists' primary motivations in their quest for a quantum theory of gravity—a theory that would predict the properties of gravitation as arising from interactions following the laws of quantum mechanics.

On a more basic level, physicists would like to know if Einstein's general relativity really is *the* theory of gravity, even where it predicts shocking deviations from classical, Newtonian theory—such as the existence of event horizons. Black holes have the twin virtues of corresponding to extraordinarily simple solutions to Einstein's equations of gravity (a black hole is completely characterized by just three numbers—its mass, charge and spin), as well as being places where gravity differs the most from Newtonian theory. Thus, black holes are prime locations for seeking evidence of deviations from Einstein's equations under extreme conditions, which could provide clues toward a quantum theory of gravity. Conversely, the equations' success near black holes will dramatically extend the regime in which we know general relativity works.

Pressing astrophysical questions about what happens in the vicinity of black holes also demand answers. Black holes are fed by infalling material such as gas and dust. The matter gains vast quantities of energy as it falls closer to the hole's horizon, producing heat 20 times more efficiently than nuclear fusion, the next most potent energy generator known. Radiation from the hot, spiraling gas makes the environment near black holes the brightest objects in the universe.

Astrophysicists can model the accreting material to some extent, but it is unclear how gas in the accretion flow migrates from an orbit at a large radius to one near the horizon and how, precisely, it finally falls into the black hole. Magnetic fields, created by charged particles moving in the accretion flow, must play a very important role in how the flow behaves. Yet we know little about how these fields are structured and how that structure affects black holes' observed properties. Although computer simulations of the entire accreting region are becoming feasible, we theorists remain decades away from true ab initio calculations. Input from observations will be vital for inspiring new ideas and deciding among competing models.

[BASICS]

LAIR OF A MONSTER

A black hole's defining feature is its event horizon, the spherical boundary of the region within which nothing can overcome the black hole's gravity and emerge. Gas accretes in a hot, luminous disk orbiting the black hole, with transitory bright spots similar to solar flares. A disk may be thin, as depicted, but can also span a large angle above and below the plane of rotation, as well as extending much farther radially. Many supermassive black holes emit bright jets at almost the speed of light.

The accretion disk's inner edge is believed to be near a circle called the innermost stable circular orbit. Any matter that strays closer to the hole will find itself in an unstable orbit and quickly plunges into the hole. At the photon orbit, light could in principle circle the black hole permanently, but in practice the tiniest disturbance would send the light spiraling in or out.

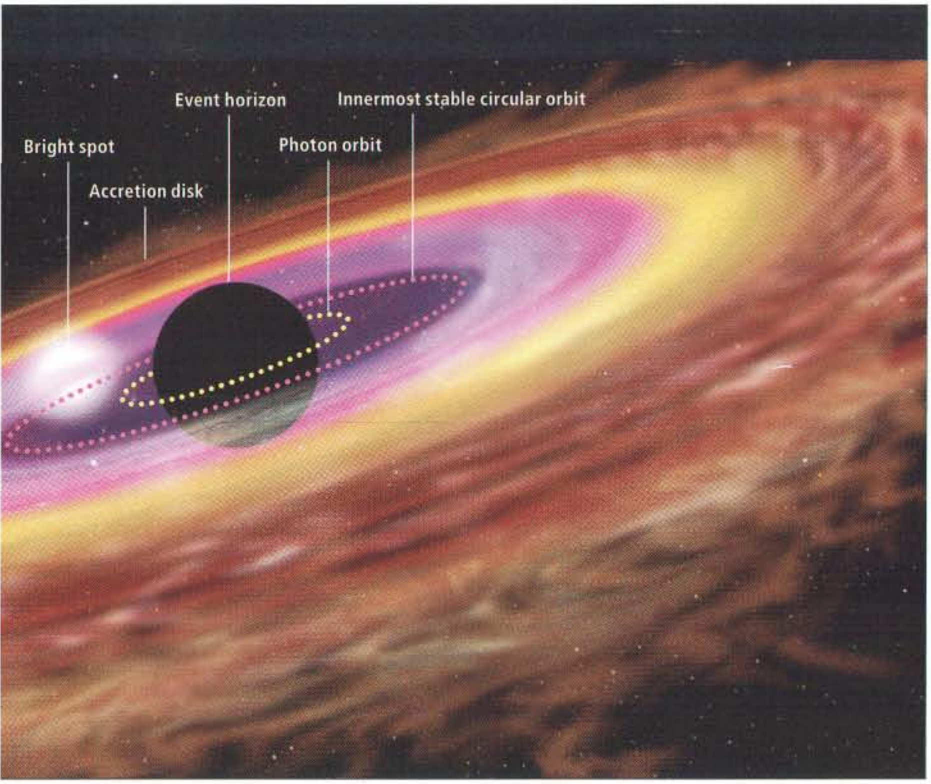
DON DIXON; JEN CHRISTIANSEN (*inset*)

Black holes are prime locations for seeking evidence of deviations from Einstein's equations of general relativity under extreme conditions.

More embarrassing to astrophysicists is our lack of understanding of black hole jets—phenomena in which the forces near a supermassive black hole somehow conspire to spew out material at ultrarelativistic speeds (up to 99.98 percent of light speed). These amazing outflows traverse distances larger than galaxies, yet they originate near the black hole as intense beams collimated tightly enough that they could thread the solar system—the eye of a galactic needle. We do not know what accelerates these jets to such high speeds or even what the jets are made of—are they electrons and protons or electrons and positrons, or are they primarily electromagnetic fields? To answer these and other questions, astronomers desperately need direct observations of the gas in a black hole's vicinity.

Stalking the Behemoth from Afar

Unfortunately, such observations are difficult for several reasons. First, black holes are extremely small by any astronomical measure. They appear to come in two main varieties: stellar-mass black holes, the remnants of dead massive stars, with typical masses of five to 15 suns,



and supermassive black holes, located at the centers of galaxies and weighing millions to 10 billion suns. A 15-solar-mass black hole's event horizon would be a mere 90 kilometers in diameter—far too tiny to be resolved at interstellar distances. Even a one-billion-sun monster would fit comfortably inside Neptune's orbit.

Second, a black hole's small size and intense gravity make for extremely fast motion—matter very near a stellar-mass black hole can complete an orbit in less than a microsecond. It takes highly sensitive instruments to observe such rapid phenomena. Finally, only the small subset of black holes that have large reservoirs of nearby gas to accrete are visible at all; the vast majority of black holes in the Milky Way are, as yet, undiscovered.

Rising to these challenges, astronomers have developed a variety of techniques that, short of providing direct images, have provided information about the properties and behavior of matter orbiting close to suspected black holes. For instance, astronomers can weigh a supermassive black hole by observing stars near it, much like using planets' orbits to weigh the sun. In distant galaxies, individual stars near a supermassive hole cannot be resolved, but the spectrum of their light indicates their distribution of velocities, which yields a mass for the hole. The supermassive black hole Sgr A* at the center of the Milky Way is close enough for telescopes to resolve individual stars near it, producing the best mass estimate of any black hole to date [*see box on page 25*]. Unfortunately, these stars are far outside the region that interests us most, where general relativistic effects become significant.

Astronomers also search for signatures of general relativity in the way that radiation emitted near a black hole varies over time. For example, the x-ray emissions of some stellar-mass black holes fluctuate in luminosity in a nearly periodic manner with periods similar to that of orbits expected to be near the inner edge of the accretion disk.

Thus far the most fruitful avenue for probing supermassive black holes has exploited the fluorescence of iron atoms on the surface of the accretion disk. The fast motion of the accretion disk carrying the iron atoms and the strong gravity of the hole combine to shift the characteristic wavelength of the fluorescence and spreads it over a band of wavelengths. Near a rapidly spinning black hole, the accretion disk itself orbits the hole faster (thanks to a general relativistic effect that drags space around with the hole's rotation), and the emission will have a telltale asymmetry. The Japanese satellites ASCA and Suzaku have observed just such emissions, which astronomers interpret as direct evidence of rapidly spinning black holes, with orbital velocities as high as one third of light speed in the accretion disks.

Information about how much spin stellar-mass black holes have has come from binary systems in which a black hole and an ordinary star orbit each other close enough for the hole to slowly feed on its companion. Analysis of the x-ray spectra and orbital parameters for a handful of such systems indicates that the holes have 65 to 100 percent of the maximum spin permitted by general relativity for a hole of a given mass; very high spin seems to be the norm.

Light (ranging from radio waves to x-rays) and energetic jets are not the only things emitted by black holes. When two black holes collide, they shake the fabric of spacetime around them, producing gravitational waves that propagate out like ripples on a pond. These ripples of spacetime should be detectable at vast distances, albeit requiring incredibly sensitive instruments. Although observatories already operating have yet to detect any gravitational waves, the method offers a revolutionary new way to study black holes. [see "Ripples in Spacetime," by W. Wayt Gibbs; SCIENTIFIC AMERICAN, April 2002].

[THE AUTHORS]

Avery E. Broderick and Abraham Loeb began collaborating in 2005 at the Institute for Theory and Computation, which Loeb now directs, at the Harvard-Smithsonian Center for Astrophysics. Broderick is currently a senior research associate at the Canadian Institute for Theoretical Astrophysics at the University of Toronto. He has been a leader in pushing for horizon-resolving imaging of supermassive black holes. Loeb is professor of astronomy at Harvard University and visiting professor at the Weizmann Institute of Science in Rehovot, Israel. He has conducted pioneering theoretical studies of the first stars, supermassive black holes and gamma-ray bursts.


COURTESY OF ALYSSA BRODERICK (*Broderick*); PUBLIC AFFAIRS OFFICE OF THE HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS (*Loeb*)

A Window with a View

Despite providing a wealth of information, none of the techniques we have described thus far offer an image of a black hole's event horizon. Now, however, thanks to very recent advances in technology, direct imaging of a black hole's horizon is imminent. The black hole to be imaged is the behemoth in our backyard, Sgr A*. At a distance of only 24,000 light-years, Sgr A* occupies the largest disk on the sky of any known black hole. A 10-solar-mass black hole would have to be 1/100th as far away as the nearest star to appear as big. And although supermassive black holes much larger than Sgr A* exist, they are millions of light-years away.

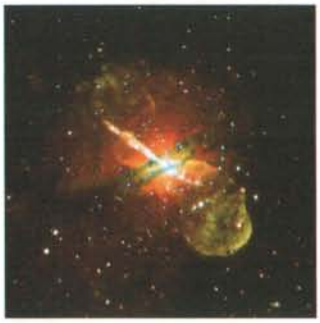
The dark silhouette of a distant black hole is more than doubled in apparent size thanks to the bending of light rays by the hole's gravity. Even so, Sgr A*'s horizon will appear to span a mere 55 microarcseconds—as small as a poppy seed in Los Angeles viewed from New York City.

The resolution of all modern telescopes, as impressive as they are, is fundamentally limited by diffraction, a wave-optics effect that occurs as light passes through the finite aperture presented by the size of the telescope. Generally, the smallest angular scale resolvable by a telescope can be decreased by making the telescope larger or by capturing shorter wavelength light. At infrared wavelengths (which, conveniently, pass through dust clouds that hide Sgr A* at visible wavelengths), an angular scale of 55 microarcseconds would require a telescope seven kilometers across. The shorter wavelengths of visible or ultraviolet light would somewhat reduce this gargantuan requirement but not by enough to be any less ridiculous. Considering longer wavelengths might seem pointless—millimeter radio waves, for instance, would require a telescope 5,000 kilometers across. But it just so happens that Earth-size radio telescopes are already operating.

A technique called very long baseline interferometry (VLBI) combines the signals detected by an array of radio telescopes sprinkled around the globe to achieve the angular resolutions that an Earth-size radio dish would achieve. Two such arrays of telescopes have been operating for more than a decade—the Very Long Baseline Array (VLBA), with dishes in the U.S. as far afield as Hawaii and New Hampshire, and the European VLBI Network (EVN), with dishes in China, South Africa and Puerto Rico, as well as Europe. You may remember seeing a much smaller system, the Very Large Array in New Mexico, in movies such as *Contact* and *2010*.

DISTANT SIGNS OF BLACK HOLES

Astrophysicists believe that black holes—too small and far away to be seen—are responsible for phenomena ranging from x-ray emissions to huge jets of material ejected from galaxy centers.



Centaurus A galaxy imaged in x-rays by the Chandra satellite shows a 13,000-light-year jet emitted by its suspected supermassive black hole. Starlike spots are stellar-mass holes consuming matter from companion stars. Red, green and blue indicate three bands of x-ray wavelengths.

Supermassive black hole presumed to be at the center of the M87 galaxy is surrounded by lobes of gas about 15,000 light-years across and shoots an ultrarelativistic jet toward us. An unseen counterjet may be sending material in the opposite direction. The Very Large Array in New Mexico took this image at two-centimeter radio wavelengths. The colors represent intensity of the signal.

Unfortunately, the VLBA and EVN are suitable only for radio wavelengths above 3.5 millimeters, corresponding to resolutions of at best 100 microarcseconds, too large to resolve Sgr A*'s horizon. Moreover, at these wavelengths, interstellar gas blurs the image of Sgr A*, just as dense fog blurs the streetlights overhead. The solution is to implement an interferometer at shorter wavelengths of millimeters and below.

These shorter wavelengths, however, suffer yet another problem: absorption by atmospheric water vapor. For this reason, millimeter and submillimeter telescopes are placed at the highest, driest sites available, such as atop Mauna Kea in Hawaii, in the Atacama Desert in Chile, and in Antarctica. When all is said and done, two useful windows generally remain open, at 1.3 millimeters and at 0.87 millimeter. An Earth-size array at these wavelengths would provide resolutions of about 26 and 17 microarcseconds, respectively, good enough to resolve the horizon of Sgr A*.

A number of millimeter and submillimeter telescopes that could be incorporated in such an array already exist—in Hawaii, scattered throughout the southwestern U.S., and in Chile, Mexico and Europe. Because astronomers built these telescopes for other purposes, adapting them for VLBI involves many technological challenges, including development of extraordinarily low-noise electronics and ultrahigh bandwidth digital recorders.

Nevertheless, a collaboration led by Sheperd S. Doeleman of the Massachusetts Institute of Technology solved these problems in 2008. The group studied Sgr A* at 1.3-millimeter wavelengths with an array of just three telescopes, in Arizona, California and on Mauna Kea. Such a small number of telescopes is insufficient to generate an image, but the researchers successfully resolved Sgr A* in that their data indicated that it had bright regions only 37 microarcseconds in size, two thirds of the horizon's size. Additional telescopes should make it possible to produce images of the event horizon's dark silhouette.

Already the recent millimeter-VLBI observations make it exceedingly difficult for Sgr A* not to have a horizon. Accretion onto a black hole and onto horizonless objects differ in a fundamental way. In both cases, the accreting material accrues vast amounts of energy during its infall. In the absence of a horizon, this energy is converted to heat where the accreting material finally settles and is subsequently emitted as radiation, producing a characteristic thermal spectrum visible to outside observers. In contrast, for black holes,

SCIENCE SOURCE (*Centaurus A*); NATIONAL RADIO ASTRONOMY OBSERVATORY/NATIONAL SCIENCE FOUNDATION (*M87*)

infalling material can carry any amount of energy across the horizon, which will hide it forever.

For Sgr A*, we can use its total luminosity to estimate the infall rate of accreting material. The millimeter-VLBI observations place a tight limit on the maximum possible size of the accretion flow's inner edge and thus on how much energy has been liberated in the flow's fall to that point. If Sgr A* does *not* have a horizon (and so is not a black hole), the surplus energy must be radiated when the accreting material comes to rest, emitting primarily in the infrared. Despite careful observations, astronomers have not found any thermal infrared emission from Sgr A*. The only way to reconcile this discrepancy without a horizon is for the material to radiate away all the excess energy as it plummets inward, but that would require absurdly high radiative efficiencies.

Portrait of a Monster

We, among other theorists, have been very busy trying to predict what observers might see when VLBI produces images of Sgr A* in the next few years. Generically, a black hole casts a silhouette on the wallpaper of emissions by nearby accreting gas. This "shadow" arises because the black hole swallows light rays coming toward the observer from just behind it. Meanwhile the bright region around the "shadow" is supplemented by other light waves from behind the black hole that just miss the horizon. Strong gravitational lensing bends light rays so that even material directly behind the black hole will contribute to the light around the dark region. The resulting silhouette is what is meant by a "portrait of a black hole," a fitting picture in which the black hole truly is black.

This shadow will not be a circular disk, primarily because of the extreme orbital velocities of the gas, which approach the speed of light. The emission from such fast-moving matter will be Doppler-shifted and concentrated in a narrow cone in the direction of motion, which substantially brightens the emission from the approaching side of the orbiting gas and dims the receding side, producing a bright crescent instead of a full, bright ring around a disklike silhouette. This asymmetry disappears only if we happen to be looking along the disk's axis of rotation.

The spin of the black hole itself, which may have a different axis of rotation than the accretion disk, has a similar effect. Such images will therefore allow astronomers to determine the direction of the black hole spin and the inclination of the accretion disk relative to it. Equally important for astrophysics, the data will provide invaluable observational input into accretion theory, settling once and for all the gas's density and the geometry of the accretion flow's inner edge.

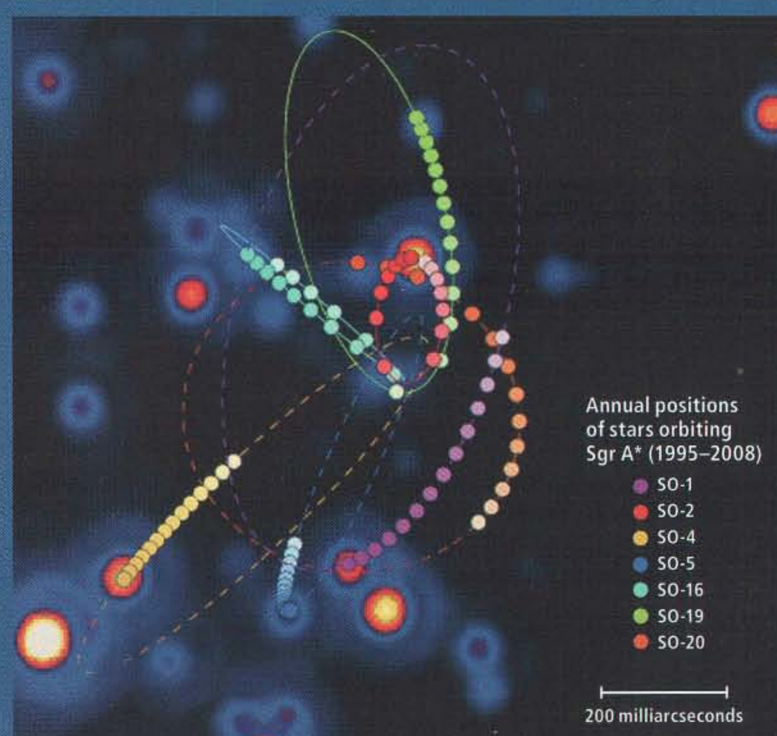
Sgr A* is the only supermassive hole close enough that telescopes can resolve the individual stars nearest to it.

Other supermassive black holes should also be within range of VLBI and can be compared with Sgr A*. We recently showed that the second-best target is the black hole believed to lie at the center of the giant elliptical galaxy M87. This black hole is 55 million light-years distant, and until recently astronomers' standard estimate of its mass was about three billion suns, giving it an expected silhouette somewhat less than half the size of Sgr A*'s. In June of this year, however, Karl Gebhardt of the University of Texas at Austin and Jens Thomas of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, used the most recent data and updated models of M87's distribution of stars and dark matter to determine a black hole mass of 6.4 billion

[SAGITTARIUS A*]

CLOSING IN ON THE GIANT

Until recently, observations of the motions of stars near the Milky Way's center have been the closest that astronomers have come to observing the event horizon of the black hole Sgr A*. The stars' orbits (*dashed lines*) reveal that they are in the thrall of a very compact object with a mass of 4.5 million suns. Colored dots mark the stars' positions each year from 1995 to 2008. The background is a 2008 infrared image of the stars (and others). The star S0-16 comes closest to Sgr A*—within seven light-hours—but even that distance remains 600 times larger than the event horizon's radius.



ANDREA GHEZ *U.C.L.A. Galactic Center Group*; DATA SETS OBTAINED WITH THE W. M. KECK TELESCOPES

[IMAGING]

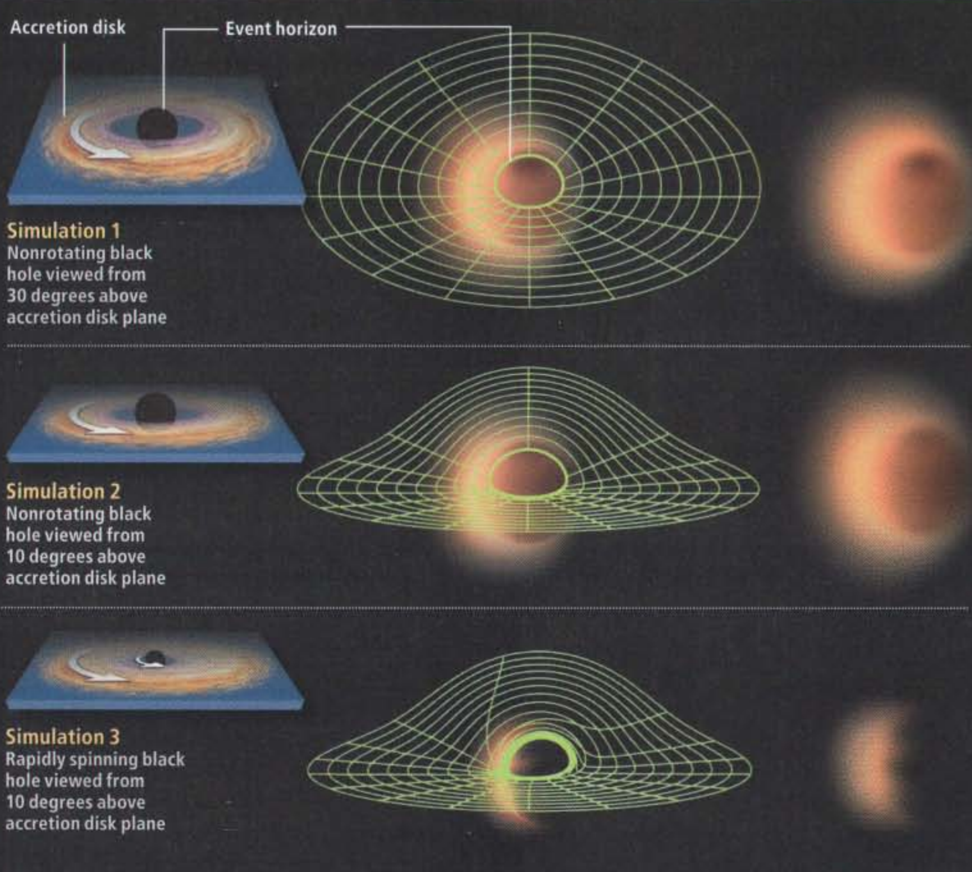
Shooting the Beast

Astronomers are developing several radio telescope arrays to form a globe-spanning network of observatories (*right*) that can observe Sgr A* and its immediate surroundings at wavelengths near 0.87 and 1.3 millimeters—two "windows" that are not excessively absorbed by Earth's atmosphere or scattered by interstellar gas. The size of the network will permit observations with sufficient resolution to produce images of Sgr A*'s event horizon.

The appearance of Sgr A* should reveal information about the orientation of the black hole's accretion disk along our line of sight and how fast the black hole is spinning—two of the most basic facts to be learned about the Sgr A* system and vital for understanding whatever else is observed about it (*below*). On occasions when a bright spot flares up in the accretion disk, gravitational lensing by the black hole will form multiple subimages of the spot (*opposite page*). If these subimages can be resolved, they will provide detailed information about the gravitational field near the black hole, which will stringently test the predictions of general relativity.

COLLECTING DATA

The Combined Array for Research in Millimeter-Wave Astronomy (CARMA; *above*), located at Cedar Flat, Calif., is one of several radio telescope arrays astronomers are developing to observe Sgr A*'s event horizon. A network of such observatories (*left*) separated by baselines thousands of kilometers long (*lines*) can exploit a technique called very long baseline interferometry to produce images with resolutions as fine as those that would be possible with a radio dish the size of Earth. Four arrays (*green*) are ready to be used together, two (*pink*) are under development, and the last (*blue*) needs only to be adapted for observations at submillimeter wavelengths.

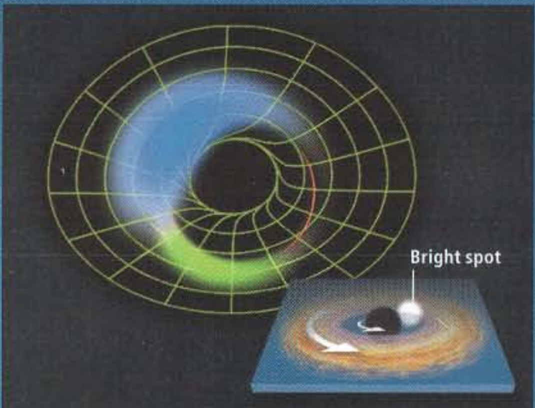


WHAT THE SILHOUETTE CAN REVEAL

Simulations show how an accretion disk around Sgr A* would appear depending on the orientation of its accretion disk and the magnitude of its spin. The rightmost trio of images includes the blurring effects of interstellar gas.

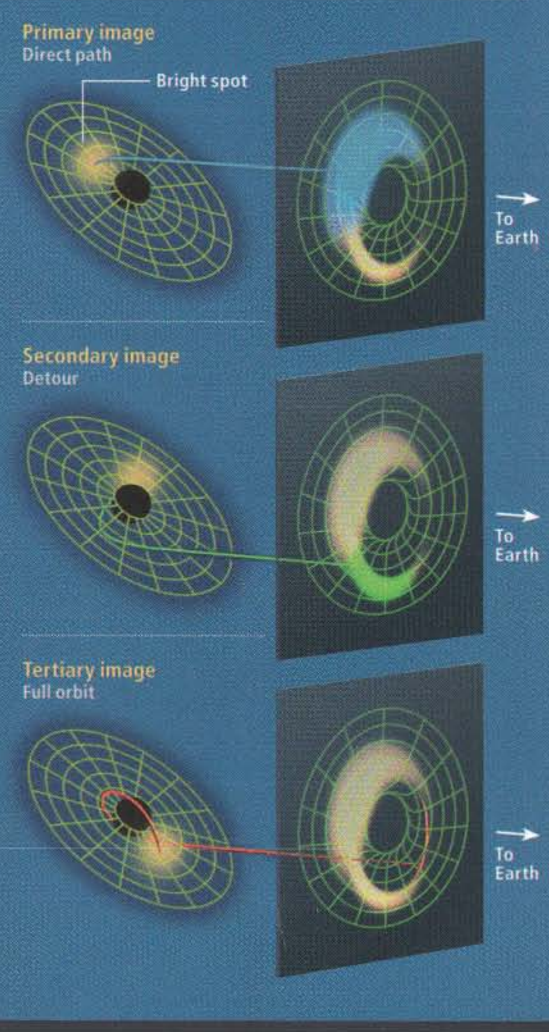
The green coordinate grid is in the plane of the accretion disk, centered on the black hole. The grid's innermost ring is at the black hole's event horizon. Bending of light rays by the hole's gravity, known as gravitational lensing, distorts the grid's appearance and also magnifies the hole's silhouette. Because the accretion disk orbits the hole at velocities approaching the speed of light, special relativistic effects come into play, making it much brighter on the side moving toward us (*here on left side of event horizon*). In the bottom image, the black hole's large, angular momentum causes additional deflection of light, further distorting our view of the equatorial plane and dramatically changing the appearance of the accreting gas.

Thus, comparing images of Sgr A* with simulations can reveal the system's orientation and the black hole's spin and can also provide—from the silhouette's size—a new measurement of the hole's mass.



MEASURING GRAVITY WITH LENSED IMAGES
Astronomers can measure gravity very near a black hole by analyzing multiple subimages (produced by gravitational lensing) of a bright spot in an accretion disk. Shown above is a simulated image of a bright spot near a moderately rotating black hole, colored to mark its three constituent subimages, which are explained in the diagrams below.

The primary image (*blue region*) forms from radio waves that traveled from the spot along the most direct path to Earth (*blue line*). Thanks to the hole's intense gravity, some rays the spot emitted earlier take a detour around the hole (*green line*) and reach Earth at the same time, forming the secondary image (*green region*). Rays that were emitted even earlier and execute a full orbit around the black hole (*red line*) generate the barely visible tertiary image (*red region*). Because the positions and shapes of the subimages depend on how gravity bends light in a variety of locations very close to the hole, analysis of the full image can reveal if general relativity correctly describes gravity there.



suns—enough to make its silhouette about three-quarters the diameter of Sgr A*'s.

In many respects, M87 is a more interesting and promising target than Sgr A*. It has a vigorous jet that extends 5,000 light-years; resolving the jet-launching region will provide critical information for theorists' efforts to understand these ultrarelativistic outflows. Unlike Sgr A*, M87 lies in the Northern Hemisphere sky, making it more amenable to VLBI using existing observatories, relatively few of which are in the south. Furthermore, with the M87 black hole being 2,000 times the size of Sgr A*, dynamical changes will occur on timescales of days instead of minutes. The orbital period near the accretion disk's inner edge will be 0.5 to five weeks (depending on the hole's spin). Obtaining sequences of images of unfolding events should be much easier with M87. Finally, high-resolution images will most likely suffer less blurring of the kind inflicted by interstellar gas between us and Sgr A*. To date, the best VLBI images of M87, taken at wavelengths of two to seven millimeters, have a resolution of about 100 microarcseconds, more than double the size of the expected silhouette.

For both Sgr A* and M87, an exciting prospect in the long run will be the possibility of imaging flare-ups that are seen in their emission from time to time. If some of these flares are caused by bright spots in the accretion flow, as most theorists expect, they can be exploited to map out the spacetime around the horizon in greater detail. The main image of each spot will be accompanied by additional images, corresponding to light rays that reach the observer by circuitous routes around the hole [*see box at left*]. The shapes and positions of these higher-order images encode the structure of the spacetime near the black hole. They will, in effect, provide independent measurements of that structure at the different locations traversed by each image's bundle of light rays. Taken together, these data will sternly test general relativity's predictions for the behavior of strong gravity near black holes.

Black hole observations are entering a new golden era. Almost a century after Einstein conceived of general relativity, we are finally in a position to test whether this theory correctly describes gravity in the extreme environments of black holes. Direct imaging of black holes will provide a new test bed for comparing Einstein's theory with its alternatives. When images of Sgr A* and M87 become available, we will be able to investigate the spacetime near black holes in detail, without sacrificing cell phone technicians. ■

TOM LOWE *Timescapes.org* (CARMA); GEORGE RETSECK (*array globe*); COURTESY OF AVERY E. BRODERICK (*computer simulations*); JEN CHRISTIANSEN (*illustrations*)

Thanks to gravitational lensing, even material directly behind the black hole will contribute to the light around the silhouette.

➡ MORE TO EXPLORE

Event-Horizon-Scale Structure in the Supermassive Black Hole Candidate at the Galactic Centre. Sheperd S. Doeleman et al. in *Nature*, Vol. 455, pages 78–80; September 4, 2008.

Imaging the Black Hole Silhouette of M87: Implications for Jet Formation and Black Hole Spin. Avery E. Broderick and Abraham Loeb in *Astrophysical Journal*, Vol. 697, pages 1164–1179; June 1, 2009.

The Event Horizon of Sagittarius A*. Avery E. Broderick, Abraham Loeb and Ramesh Narayan in *Astrophysical Journal*, Vol. 701, pages 1357–1366; August 20, 2009.

Imaging an Event Horizon: Submm-VLBI of a Super Massive Black Hole. Sheperd S. Doeleman et al. in *ASTRO2010 Decadal Review*. Online at **arxiv.org/abs/0906.3899**

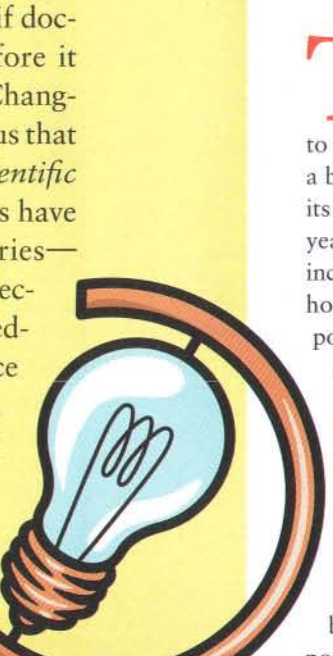
Inside Black Holes. Andrew J. S. Hamilton. Includes animations of descent into a black hole. Online at **jilawww.colorado.edu/~ajsh/insidebh**

U.C.L.A. Galactic Center Group Web site: **www.astro.ucla.edu/~ghezgroup/gc**

World Changing Ideas

20 ways to build a cleaner, healthier, smarter world

What would happen if solar panels were free? What if it were possible to know everything about the world—not the Internet, but the living, physical world—in real time? What if doctors could forecast a disease years before it strikes? This is the promise of the World Changing Idea: a vision so simple yet so ambitious that its full impact is impossible to predict. *Scientific American's* editorial and advisory boards have chosen projects in five general categories—Energy, Transportation, Environment, Electronics and Robotics, and Health and Medicine—that highlight the power of science and technology to improve the world. Some are in use now; others are emerging from the lab. But all of them show that innovation is the most promising elixir for what ails us. *—The Editors*



SCI AM

More ...

Find additional information about this topic at **www.ScientificAmerican.com/dec2009**

ENERGY

The No-Money-

A new wave of start-ups wants to install rooftop solar panels on your house. Upfront cost: nothing

BY CHRISTOPHER MIMS

The biggest thing stopping the sun is money. Installing a rooftop array of solar panels large enough to produce all of the energy required by a building is the equivalent of prepaying its electricity bill for the next seven to 10 years—and that's after federal and state incentives. A new innovation in financing, however, has opened up an additional possibility for homeowners who want to reduce their carbon footprint and lower their electric bills: get the panels for free, then pay for the power as you go.

The system works something like a home mortgage. Organizations and individuals looking for a steady return on their investment, typically banks or municipal bond holders, use a pool of cash to pay for the solar panels. Directly or indirectly, homeowners buy the electricity produced by their own rooftop at a rate that is less, per kilowatt-hour, than they would pay for electricity from

CHRISTOPH NIEMANN

Down Solar Plan

the grid. Investors get a safe investment—the latest generation of solar-panel technology works dependably for years—and homeowners get a break on their monthly bills, not to mention the satisfaction of significantly reducing their carbon footprint. "This is a way to get solar without putting any money down and to start saving money from day one. That's a first," says SolarCity co-founder Peter Rive.

SolarCity is the largest installer of household solar panels to have adopted this strategy. Founded in 2006 by two brothers who are also Silicon Valley–based serial entrepreneurs, SolarCity leases its panels to homeowners but gives the electricity away for free. The net effect is a much reduced utility bill (customers still need utility-delivered power when the sun isn't out) plus a monthly SolarCity bill. The total for both comes out to less than the old bill. SunRun in San Francisco offers consumers a similar package, except that the company sells customers the electricity instead of leasing them the panels.

Cities such as Berkeley and Boulder are pioneering their own version of solar-panel financing by loaning individuals the entire amount required to pay for solar panels and installation. The project is paid for by municipal bonds, and the homeowner pays back the loan over 20 years as a part of the property tax bill. The effect is the same whichever route a consumer takes: the new obligation, in the form of taxes, a lease or a long-term contract for electricity, ends up costing less than the existing utility bill.

"What we're really seeing is a transition in how we think about buying energy goods and services," says Daniel M. Kammen, director of the Renewable and Appropriate Energy Laboratory at the University of California, Berkeley. Kammen, who did the initial analysis on Berkeley's financing model, believes that by turning to financing, consumers can overcome the inherent disadvantage renewables have when compared with existing energy sources: the infrastructure for power from the grid has already been paid for and, in many cases, has been subsidized for decades.

All three approaches are rapidly expanding across the country. Despite the Berkeley program being less than two years old, 10 different states have passed legislation allowing their cities to set up a Berkeley-style bond-financed loan program. With the passage of the Waxman-Markey climate bill, the option for cities to set up these programs would become federal law. SunEdison in Maryland is currently active in nine states. SolarCity, which has more than 4,000 customers, is active in California, Arizona and Oregon and has promised to announce additional states after the new year.

Right now it is not possible to lower the overall cost of rooftop solar to "grid parity," that is, to the same price as electricity from local utility companies, without federal subsidies such as the investment tax credit, which lowers the tax bill of banks financing these projects. Those subsidies, which amount to 30 percent of the cost of a solar installation, are guaranteed for at least eight years. By then, SolarCity and its competitors claim they won't need them.

"Grid parity is driven by multiple factors," says Attila Toth, vice president of marketing at SunEdison, including the cost of capital, the cost of panels and their installation, and the intensity of sunlight in a given region. "It will occur in different states at different times, but, for example, we expect that California will be one of the first states in the U.S. to get to grid parity, sometime between three and five years from now."

While the cost of electricity from fossil fuels has increased 3 to 5 percent a year for the past decade, the cost of solar panels has fallen on average 20 percent for every doubling of its installed base. Grid parity is where these trend lines cross—after that, solar has the potential to power more than just homes. It's hardly a coincidence that Elon Musk, head of electric car company Tesla Motors, sits on SolarCity's board of directors.

COURTESY OF SOLARCITY

ENERGY

MORE IDEAS TO WATCH

BY CHRISTOPHER MIMS

THE GASOLINE GARDEN

It is the next step for biofuels: genetically engineered plant life that produces hydrocarbons as a by-product of its normal metabolism. The result will be fuel—common gasoline, even—using nothing but sunlight and CO_2. In July, Exxon Mobil announced plans to spend more than $600 million in pursuit of algae that can accomplish the task. Joule Biotechnologies claims to have already succeeded, although the company has yet to reveal any details of its proprietary system.

HOT NUKES

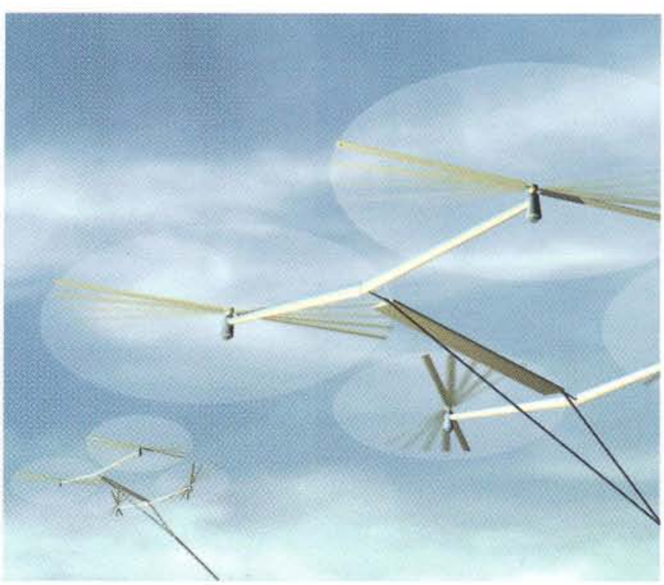
Uranium and plutonium are not the only fuels that can power a nuclear reactor. With an initial kick from more traditional fissile materials, thorium can set up a self-sustaining "breeder" reaction that produces uranium 233, which is well suited to nuclear power generation. The process has the added benefit of being resistant to nuclear proliferation, because its end products emit enough gamma rays to make the fuel dangerous to handle and easy to track.

SAVE ENERGY WITH INFORMATION

Studies show that simply making customers aware of their energy use lowers it by 5 to 15 percent. Smart meters allow customers to track their energy consumption minute by minute and appliance by appliance. Countless start-ups are offering the devices, and Google and Microsoft are independently partnering with local utilities to allow individuals to monitor their power usage over the Web.

WIND POWER FROM THE STRATOSPHERE

According to a Stanford University study released in July, the high-altitude winds that constantly blow tens of thousands of feet above the earth hold enough energy to supply all of human civilization 100 times over. California's Sky WindPower has proposed harvesting this energy by building fleets of giant, airborne, ground-tethered windmills (*below*), while Italy's Kite Gen proposes to accomplish the same feat using kites.



TRANSPORTATION

Delivering the U.S. from

Plug-in hybrid trucks are improving the long view of the short haul

BY AMANDA SCHUPAK

Cargo trucks gulp about 40 percent of the fuel pumped in the U.S. While most consumer attention focuses on improving the fuel economy of consumer vehicles, a major opportunity goes rumbling by. "Folks do not realize that the fuel use of even a small truck is equal to many, many cars," says Bill Van Amburg, senior vice president of Calstart, a clean transportation technology nonprofit, and director of the Hybrid Truck Users Forum. "A utility truck as a hybrid would reduce more petroleum than nine Priuses."

Some 1,300 commercial hybrids on the road today get up to twice the fuel efficiency of their conventional counterparts. But these traditional hybrids are inherently limited. They make more efficient use of petroleum-based fuel by capturing some of the energy lost during braking.

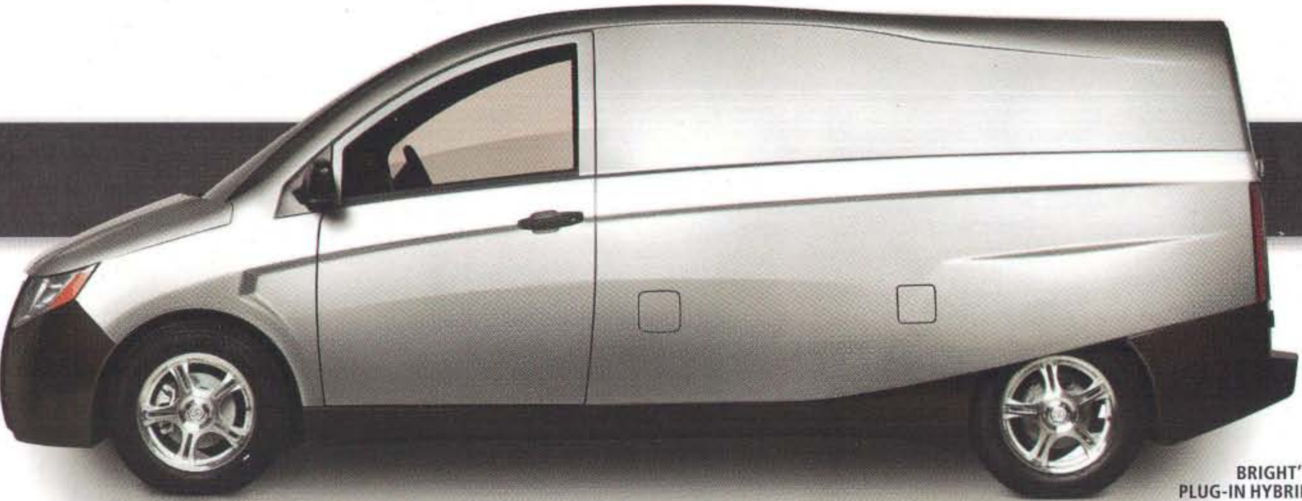
Plug-in hybrids, on the other hand, draw energy from the grid. They can drive for miles—in many cases, an entire day's route—without using any fossil fuel at all. This shifts energy demand away from petroleum and toward grid-based sources. (Last year zero-carbon renewables and nuclear supplied 30 percent of all electric power in the U.S.)

In many ways, plug-in hybrid technology makes more sense for delivery trucks than for consumer sedans. A cargo truck runs a short daily route that includes many stops to aid in regenerative braking. Most of the U.S. Postal Service's 200,000-plus mail trucks, for example, travel fewer than 20 miles a day. In addition, fleet vehicles return nightly to storage lots that have ready access to the 120- or 240-volt outlets required to charge them.

The Department of Energy recently launched the nation's largest commercial plug-in hybrid program, a $45.4-million project to get 378 medium-duty vehicles on the road in early 2011. The trucks, which will go to 50 municipal and utility fleets, will feature a power system from Eaton, a large manufacturer of electrical components, on a Ford F-550 chassis. (For its part, Ford will wait for the market to prove itself before designing its own commercial plug-ins.) "These are going to start breaking free in 2011," says Paul Scott, president of the Electric Vehicle Association of Southern California.

Start-up company Bright Automotive has a more ambitious plan. It aims to replace at least 50,000 trucks with plug-in hybrids by 2014. Bright's IDEA prototype (*above right*) travels 40 miles on battery power before switching to a four-cylinder engine that gets 40 miles to the gallon. The streamlined aluminum body has the payload of a postal truck yet is far more aerodynamic. The truck weighs as much as a midsize sedan.

COURTESY OF PACIFIC GAS AND ELECTRIC COMPANY (*SmartMeter*); DON FOLEY; SOURCES: BEN SHEPARD *SkyWindPower Corporation* (*tethered windmills*)



BRIGHT'S PLUG-IN HYBRID

John E. Waters, Bright Automotive's founder and the former developer of the battery system for General Motors's groundbreaking EV1 electric car, says that each IDEA would save 1,500 gallons of fuel and 16 tons of carbon dioxide emissions a year over a standard utility truck. Waters says he is ready to begin assembly in his U.S. plant once a pending $450-million federal loan comes through.

Despite the appeal of the carbon savings, the fleet owners who are the trucks' primary customers have more practical considerations. Bright's executives are coy about the IDEA's eventual price tag but assert that a customer with 2,000 trucks driving 80 miles a day five days a week could save $7.2 million a year. Right now that is probably not enough to justify large-scale purchases without additional rebates—or a price on carbon. Van Amburg estimates that going hybrid currently adds $30,000 to $50,000 in upfront costs per vehicle, although that figure should come down as production volumes increase.

Improved battery technology will also help. Today the IDEA's 13-kilowatt-hour lithium-ion battery pack accounts for nearly a quarter of the vehicle's total cost. Much of the research being done for the batteries going into the Chevy Volt and other consumer plug-ins should also be applicable to commercial batteries. "For all the good we all want to do," says David Lauzun, Bright's vice president of product development, "these vehicles will not take over the world until it becomes the economic choice—'I have to have them because it saves me money.'"

TRANSPORTATION

Bus Rapid Transit

Subwaylike bus lines mobilize the urban future BY MICHAEL MOYER

For the first time in human civilization, more people now live in urban areas than in the countryside. This shift creates a number of dilemmas, not least of which is how to move people within the world's rapidly growing metropolises. Pollution and traffic point away from car-based options, while light-rail systems are slow to construct and prohibitively expensive. One disarmingly simple—and cheap—possibility is Bus Rapid Transit, which is engineered to operate like a subway on wheels. In these systems, concrete dividers on existing roads separate high-capacity buses from the rest of traffic. Riders pay before boarding, then wait in enclosed stations. When a bus arrives, sliding partitions open to allow riders to board from a platform that is level with the bus floor. The traffic-free thoroughfares, quick boarding times, and modern, comfortable stations resemble light-rail systems more than the chaos of typical bus travel. In Bogotá, Colombia, which has had seven Bus Rapid Transit lines in operation since 2001 (*right*), the buses handle 1.6 million trips a day. Its success has allowed the city to remove 7,000 private buses from the city, reducing consumption of bus fuel and its associated pollution by more than 59 percent.

COURTESY OF BRIGHT AUTOMOTIVE (*van*); SCOTT DALTON *Redux Pictures* (*bus lines*)

ENVIRONMENT

Ocean Overhaul

Marine zoning is a bold remedy for sick seas BY SARAH SIMPSON

These days not even many politicians deny that the oceans are ill. Protecting the health of coastal waters is now a matter of national policy in dozens of countries, including the U.S., and world leaders are beginning to prescribe a revolutionary remedy that conservationists have been promoting for years: marine planning and zoning.

The idea is a natural extension of management policies that have guided the development of cities and landscapes for nearly a century. Porn shops aren't next to preschools, after all, and drilling rigs aren't the centerpieces of national parks. Similarly, zoning advocates envision a mosaic of regional maps in which every watery space on the planet is designated for a particular purpose. Drilling and mining would be allowed only in certain parts of the ocean; fishing in others. The most critically threatened areas would be virtually off-limits.

Whereas people can easily find maps telling them what they can do where on land, the marine realm is a hodgepodge of rules emanating from an army of agencies, each one managing a single use or symptom. In the U.S., for example, one body regulates commercial fishing, usually a single species at a time. Another group manages toxic substances, still another seabed mining, and so on—some 20 federal agencies in all. They tend to make decisions without regard to what the others are doing, explains Duke University marine ecologist Larry B. Crowder. "Imagine all of the medical specialists visiting a patient in intensive care one at a time and never talking to one another," he says. "It's a wonder that the oceans aren't in worse shape than they are now."

Ocean advocates such as Crowder eagerly await the final recommendations of a special task force President Barack Obama charged with presenting a plan for overhauling management of U.S. waters, which extend 200 nautical miles offshore. The scope of such an undertaking is huge: the U.S. controls 4.4 million square miles of seascape, making the country's underwater real estate 25 percent larger than its landmass. The committee's preliminary report, released in September, suggests that the best way to minimize harmful human impacts on the oceans is to manage regions rather than symptoms.

CHRISTOPH NIEMANN

Many environmentalists are hopeful that such plans will be implemented through the marine equivalent of municipal zoning, which would give them some influence in areas where they now have none. In zones where conservation is designated as the dominant activity, fishing and industrial activities such as mining would no longer have free rein. Under current rules, about the only way a conservation group can block a project it deems harmful—say, a new site for offshore drilling—is through expensive litigation.

So far, though, the president's task force has been careful not to suggest that ocean zoning will be the only treatment plan, in great part because any effort to restrict commercial interests is bound to meet stiff opposition. "Zoning isn't anybody's favorite exercise," notes John C. Ogden, director of the Florida Institute of Oceanography at the University of South Florida at Tampa. "Someone's ox is always getting gored." Most resistant to such change will most likely be the traditional users of the open ocean—namely, commercial fisheries and the petroleum industry. "They've had the place to themselves for a long time," Ogden says.

Ogden and others are quick to point out, however, that zoning practices can benefit commerce as much as conservation. By giving up access to certain areas, industries gain the security of knowing their activities would be licensed in a more predictable and less costly manner than they are today, explains Josh Eagle, associate professor at the University of South Carolina School of Law. Now an oil company can apply for permits to drill virtually anywhere, but it takes on a significant financial risk each time. The business may dump millions of dollars into researching

a new facility only to have a lawsuit derail it at the last moment. When opposing parties have more or less equal voices early in the planning process, Eagle says, they are less inclined to block one another's activities once zones are drawn on a map.

Whether the final report of the president's task force will promote ocean zoning explicitly is uncertain. But the group has already promised to overhaul the structure of ocean governance by proposing the creation of a National Ocean Council, whose job it will be to coordinate efforts of the myriad federal agencies now in charge.

The move comes just in time. Just as society is beginning to appreciate the enormous efforts it will take to preserve the health of the oceans, it must ask more of them—more energy, more food, and better resilience to coastal development and climate change. The reason the oceans are in trouble is not what people put in and take out. It is a failure of governments to manage these activities properly. Says Crowder: "We have to treat the oceans holistically, not one symptom at a time."

ENVIRONMENT

The Power of Garbage


INSIDE A GASIFICATION CHAMBER

Trapped lightning could help zap trash and generate electricity BY JOHN PAVLUS

Trash is loaded with the energy trapped in its chemical bonds. Plasma gasification, a technology that has been in development for decades, could finally be ready to extract it.

In theory, the process is simple. Torches pass an electric current through a gas (often ordinary air) in a chamber to create a superheated plasma—an ionized gas with a temperature upward of 7,000 degrees Celsius, hotter than the surface of the sun. When this occurs naturally we call it lightning, and plasma gasification is literally lightning in a bottle: the plasma's tremendous heat dissociates the molecular bonds of any garbage placed inside the chamber, converting organic compounds into syngas (a combination of carbon monoxide and hydrogen) and trapping everything else in an inert vitreous solid called slag. The syngas can be used as fuel in a turbine to generate electricity. It can also be used to create ethanol, methanol and biodiesel. The slag can be processed into materials suitable for use in construction.

In practice, the gasification idea has been unable to compete economically with traditional municipal waste processing. But the maturing technology has been coming down in cost, while energy prices have been on the rise. Now "the curves are finally crossing—it's becoming cheaper to take the trash to a plasma plant than it is to dump it in a landfill," says Louis Circeo, director of Plasma Research at the Georgia Tech Research Institute. Earlier this summer garbage-disposal giant Waste Management partnered with InEnTec, an Oregon-based start-up, to begin commercializing the latter's plasma-gasification processes. And major pilot plants capable of processing 1,000 daily tons of trash or more are under development in Florida, Louisiana and California.

Plasma isn't perfect. The toxic heavy metals sequestered in slag pass the Environmental Protection Agency's leachability standards (and have been used in construction for years in Japan and France) but still give pause to communities considering building the plants. And although syngas-generated electricity has an undeniably smaller carbon footprint than coal—"For every ton of trash you process with plasma, you reduce the amount of CO_2 going into the atmosphere by about two tons," Circeo says—it is still a net contributor of greenhouse gases.

"It is too good to be true," Circeo admits, "but the EPA has estimated that if all the municipal solid waste in the U.S. were processed with plasma to make electricity, we could produce between 5 and 8 percent of our total electrical needs—equivalent to about 25 nuclear power plants or all of our current hydropower output." With the U.S. expected to generate a million tons of garbage every day by 2020, using plasma to reclaim some of that energy could be too important to pass up.

ENVIRONMENT

MORE IDEAS TO WATCH

BY JOHN PAVLUS

CEMENT AS A CARBON SPONGE

Traditional cement production creates at least 5 percent of global carbon dioxide emissions, but new materials could create carbon-neutral cement. Start-up Novacem, supported by Imperial College London, uses magnesium oxide to make cement that naturally absorbs CO_2 as it hardens. California-based Calera uses seawater to sequester carbon emissions from a nearby power plant in cement.

THE NEW HONEYBEE

Colony collapse disorder (CCD) has killed more than a third of honeybee colonies since 2006. Farmers who depend on bees to pollinate such crops as almonds, peaches and apples are looking to the blue orchard bee to pick up the slack.

One efficient *Osmia lignaria* (*left*) can pollinate as much territory as 50 honeybees, but the bees are harder to cultivate because of their solitary nature. These pinch hitters won't completely replace honeybees, but as scientists continue to grapple with CCD, they could act as an agricultural safety net.

SALTWATER CROPS

As the world's freshwater supply becomes scarcer and food production needs balloon, salt-tolerant crops could ease the burden. Researchers at Australia's University of Adelaide used genetic engineering to enhance a model crop's natural ability to prevent saline buildup in its leaves, allowing the plant to thrive in conditions that would typically wither it. If the same gene tweak works in cereal crops such as rice (*below*) and wheat—the researchers are testing them now—fallow lands destroyed by drought or overirrigation could become new breadbaskets.

COURTESY OF INENTECH, LLC (*plasma gasification*); COURTESY OF SCOTT BAUER *USDA* (*bee*); TOM BONAVENTURE *Getty Images* (*rice*)

The Omnipotence Machines

Tiny, ubiquitous sensors will allow us to index the physical world the way the Web maps cyberspace BY GREGORY MONE

Earlier this year Hewlett-Packard announced the launch of its Central Nervous System for the Earth (CeNSE) project, a 10-year effort to embed up to a trillion pushpin-size sensors across the planet. Technologists say that the information gathered by this kind of ubiquitous sensing network could change our knowledge of the world as profoundly as the Internet has changed business. "People had no idea the Web was coming," says technology forecaster Paul Saffo. "We are at that moment now with ubiquitous sensing. There is quite an astonishing revolution just around the corner."

The spread of versatile sensors, or "motes," and the ability of computers to analyze and either recommend or initiate responses to the data they generate, will not merely enhance our understanding of nature. It could lead to buildings that manage their own energy use, bridges that flag engineers when in need of repair, cars that track traffic patterns and detect potholes, and home security systems that distinguish between the footfalls of an intruder and the dog, to name a few.

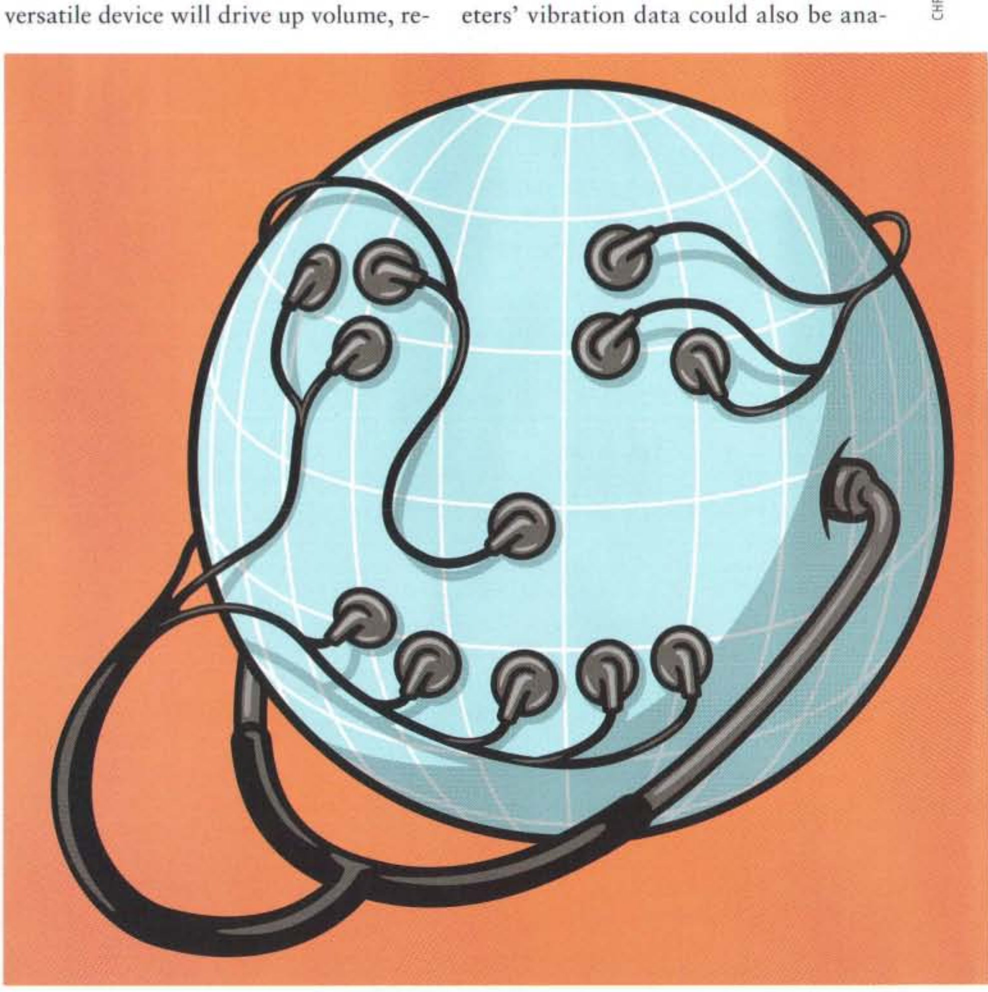
CeNSE is the boldest project yet announced, but HP is not the only organization developing the technology to make ubiquitous sensing possible. Intel is also designing novel sensor packages, as are numerous university labs.

For all the momentum in the field, though, this sensor-filled future is by no means inevitable. These devices will need to generate rich, reliable data and be rugged enough to survive tough environments. The sensor packages themselves will be small, but the computing effort required will be enormous. All the information they gather will have to be transmitted, hosted on server farms, and analyzed. Finally, someone is going to have to pay for it all. "There is the fundamental question of economics," notes computer scientist Deborah Estrin of the University of California, Los Angeles. "Every sensor is a nonzero cost. There is maintenance, power, keeping them calibrated. You don't just strew them around."

In fact, HP senior researcher Peter Hartwell acknowledges that for CeNSE to hit its goals, the sensors will need to be nearly free. That is one of the reasons why HP is designing a single, do-everything, pushpin-size package stacked with a variety of gauges—light, temperature, humidity, vibration and strain, among others—instead of a series of devices for different tasks. Hartwell says that focusing on one versatile device will drive up volume, reducing the cost for each unit, but it could also allow HP to serve several clients at once with the same sensors.

Consider his chief engineering project, an ultrasensitive accelerometer. Housed inside a chip, the sensor tracks the motion of a tiny, internal movable platform relative to the rest of the chip. It can measure changes in acceleration 1,000 times as accurately as the technology in the Nintendo Wii.

Hartwell imagines situating one of these pins every 16 feet along a highway. Thanks to the temperature, humidity and light sensors, the motes could serve as mini weather stations. But the accelerometers' vibration data could also be ana-



CHRISTOPH NIEMANN

lyzed to determine traffic conditions—roughly how many cars are moving past and how quickly. The local highway department would be interested in this information, he guesses, but there are potential consumer applications, too. "Your wireless company might want to take that information and tell you how to get to the airport the fastest," Hartwell says.

All of this gathering and transmission of data requires power, of course, and to guarantee an extended life, the HP pushpin will not rely solely on batteries. "It is going to have some sort of energy-scavenging ability," Hartwell says. "Maybe a solar panel or a thermoelectric device to help keep the battery charged."

With the power hurdle in mind, other groups are forgoing batteries altogether. At Intel Labs in Seattle, engineer Josh Smith has developed a sensor package that runs on wireless power. Like the HP pushpin, Intel's WISP, or Wireless Identification and Sensing Platform, will include a variety of gauges, but it will also draw energy from the radio waves emitted by long-range radio-frequency ID chip readers. Smith says a single reader, plugged into a wall outlet, can already power and communicate with a network of prototype WISPs five to 10 feet away—a distance that should increase.

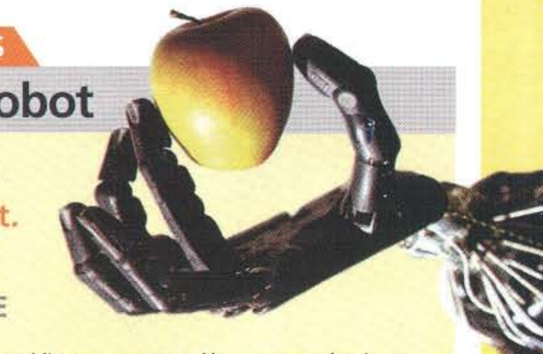
Smith cites many of the same infrastructure-related possibilities as Hartwell, along with a number of other uses. If WISPs were placed on standard household items such as cups, these tags could inform doctors about the rehabilitation progress of stroke victims. If the cups the patient normally uses remain stationary, Smith explains, then the individual probably is not up and moving around.

The potential applications for ubiquitous sensing are so broad—a physicist recently contacted him about using WISPs to monitor the temperature outside a proposed neutrino detector—that, as with the Internet, Smith says it is impossible to foresee them all. "In terms of the impact it is going to have on our lives," Hartwell adds, "you haven't seen anything yet."

JEFF J. MITCHELL Getty Images (robot hand)

ELECTRONICS AND ROBOTICS

The Do-Anything Robot



Your PC can accomplish any computing task you ask of it. Why isn't the same true for robots? BY GREGORY MONE

Robots have proved to be valuable tools for soldiers, surgeons and homeowners hoping to keep the carpet clean. But in each case, they are designed and built specifically for the job. Now there is a movement under way to build multipurpose machines—robots that can navigate changing environments such as offices or living rooms and work with their hands.

All-purpose robots are not, of course, a new vision. "It's been five or 10 years from happening for about 50 years," says Eric Berger, co-director of the Personal Robotics Program at Willow Garage, a Silicon Valley start-up. The delay is in part because even simple tasks require a huge set of capabilities. For a robot to fetch a mug, for example, it needs to make sense of data gathered by a variety of sensors—laser scanners identifying potential obstacles, cameras searching for the target, force feedback in the fingers that grasp the mug, and more. Yet Berger and other experts are confident that real progress could be made in the next decade.

The problem, according to Willow Garage, is the lack of a common platform for all that computational effort. Instead of building on the capabilities of a single machine, everyone is designing robots, and the software to control them, from the ground up. To help change this, Willow Garage is currently producing 25 copies of its model PR2 (for "Personal Robot 2"), a two-armed, wheeled machine that can unplug an appliance, open doors and move through a room. Ten of the robots will stay in-house, but 10 more will go to outside research groups, and everyone will pool their advances. This way, Berger says, if you want to build the robotic equivalent of a Twitter, you won't start by constructing a computer: "you build the thing that's new."

ELECTRONICS AND ROBOTICS

Pocket Translator

The military, short on linguists, is building smart phone–based devices to do the job BY GREGORY MONE

Sakhr Software, a company that builds automatic language translators, recently unveiled a prototype smart phone application that transforms spoken English phrases into spoken Arabic, and vice versa, in near real time. The technology isn't quite ready for your next trip to Cairo, but thanks to recent advances in machine-translation techniques, plus the advent of higher-fidelity microphones and increasing processing power in smart phones, this mobile technology could soon allow two people speaking different languages to have basic conversations.

Before the 1990s automatic translation meant programming in an endless list of linguistic rules, a technique that proved too labor-intensive and insufficiently accurate. Today's leading programs—developed by BBN Technologies, IBM, Sakhr and others as part of a Defense Advanced Research Projects Agency effort to eliminate the military's need for human translators—rely on machine-learning techniques instead. The software works from a database of parallel texts—for example, *War and Peace* in two different languages, translated United Nations speeches, and documents pulled off the Web. Algorithms identify short matching phrases across sources, and the software uses them to build statistical models that link English phrases to Arabic ones.

John Makhoul, BBN's chief scientist, says the current technology is at its best when confined to subject areas with specific phrases and terminology—translating a weather report from English into French, for example, or helping soldiers gather basic biographical information from people in the field. Makhoul envisions the first consumer applications, five years from now, being similarly constrained. A tourism-related translation app on a smart phone could help an American in Florence get directions from a non-English-speaking local, but they won't chat about Renaissance art. "It is not going to work perfectly," he says, "but it will do a pretty good job."

Know if Disease Grows Inside You

Complex diseases have complex causes. Luckily, they also leave a multitude of traces

BY MELINDA WENNER

With the exception of certain infectious diseases, few of humanity's ailments have cures. More than 560,000 Americans will die of cancer this year, and despite the 250,000 coronary bypass surgeries doctors perform annually, heart disease is still the country's number-one killer.

The hardest diseases to cure are the ones that take the longest to develop. They are the end result of decades of complex molecular interactions inside your body. Yet this complexity also presents an opportunity. Scientists have discovered that these interactions leave discernible fingerprints on the body. By unweaving the complex tapestry of molecular clues—changes in the body's proteins, nucleic acids and metabolites, collectively called biomarkers—doctors hope they will soon be able to not only detect disease but predict a coming illness in time to take action.

Biomarkers are not new. Since 1986 doctors have monitored prostate cancer by measuring blood levels of the protein known as prostate-specific antigen (PSA). But tests that rely on a single biomarker to detect disease are rare, because most disorders involve intricate changes in a collection of biomarkers.

Take schizophrenia: in January 2010 scientists will release a biomarker test that distinguishes schizophrenia from other psychiatric conditions. The test, which is being commercialized by Rules-Based Medicine, a laboratory in Austin, Tex., is based on the characteristics of about 40 blood-based proteins.

To find potentially useful biomarkers, researchers collect blood samples from thousands of healthy people and analyze them. Biomarker levels in these samples provide a baseline reading. Then they do the same for people with a specific condition such as diabetes or breast cancer. If reproducible differences emerge between the groups, scientists can use the patterns in the disease group to diagnose the same condition in others. By collecting samples over time, researchers can also go back and analyze early samples from individuals who later become ill to identify patterns indicative of early disease or high disease risk.

Biophysical Corporation, a sister company to Rules-Based Medicine, is one of several companies that has developed blood-based biomarker tests and marketed them to the public [see "The Ultimate Blood Test," by Philip Yam; SCIENTIFIC AMERICAN, June 2006]. The company searches for up to 250 biomarkers suggestive of cancer, inflammatory conditions, heart disease and other illnesses. Mark Chandler, Biophysical's chair and CEO, says that the real value of the tests lies in long-term monitoring. A person could "get a test monthly, just a finger stick, that would be able to say, we have had a serious change here that is indicative of an early-stage cancer," he explains.

Yet not all experts are convinced that the age of biomarkers is at hand. Cheryl Barton, an independent U.K.-based pharmaceutical consultant who authored a Business Insights market analysis report on biomarkers in 2006, says she remains "a little bit skeptical about how clinically useful they are." A study of 5,000 subjects published in the *Journal of the American Medical Association* in July 2009 found that six cardiovascular biomarkers were only marginally better at predicting heart disease than were standard cardiovascular risk factors, such as whether the subjects smoked or had diabetes.

Adding to the overall difficulty, a person might suffer from two or more diseases—prostate cancer and heart disease, for example. No one knows how multiple diseases might affect overall biomarker signatures or how profiles will change as other diseases develop. "When you get to be 65 or 70, almost everybody has other conditions," Chandler says. "We don't know how to deal with that right now." And scientists still need to discern which biomarkers are truly relevant to disease—a difficult task when working with blood, which contains tens of thousands of proteins at

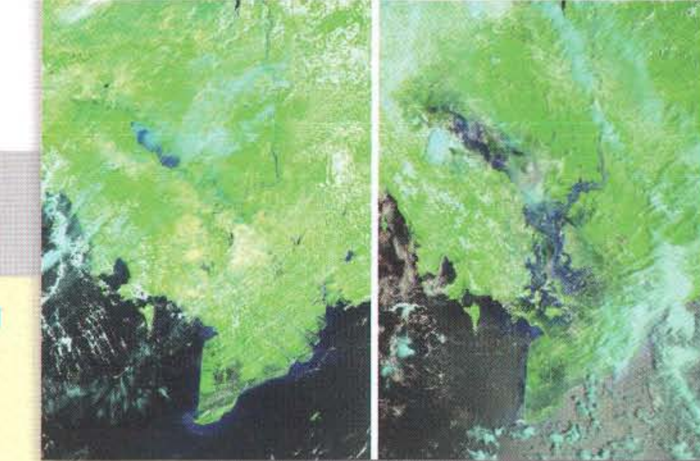
CHRISTOPH NIEMANN

HEALTH AND MEDICINE

Satellites Diagnose Disease Outbreaks

Space-based data are helping to track and predict the spread of deadly diseases

BY KATHERINE HARMON



WATERY OMEN: Environmental changes such as flooding (*right*) on the Mekong Delta in Vietnam may portend waves of disease.

NASA IMAGE CREATED BY JESSE ALLEN; EARTH OBSERVATORY USING DATA OBTAINED FROM MODIS RAPID RESPONSE TEAM

Many contagious diseases spread through carriers such as birds and mosquitoes. These vectors in turn move with heat and rainfall. With this in mind, researchers have begun to use satellite data to monitor the environmental conditions that lead to disease. "Ideally, we could predict conditions that would result in some of these major outbreaks of cholera, malaria, even avian flu," says Tim Ford of the University of New England at Biddeford and co-author of a paper on the subject published this past September in *Emerging Infectious Diseases.*

Satellite data have already been used to map the advance of the H5N1 avian influenza in Asia. The domestic duck, a common inhabitant of Southeast Asia's rice paddies, is one of the main carriers of the disease. Xiangming Xiao, associate director of the University of Oklahoma's Center for Spatial Analysis, uses satellite images to map agricultural patterns in the region. These maps show where the ducks are most likely to live and thus where the avian influenza is most likely to spread.

Migratory birds also carry the virus, but their travel patterns are more difficult to predict. Xiao and his colleagues combine the satellite imagery with satellite-gathered surface-temperature data to estimate the birds'—and thereby the virus's—trajectory. Computer models then link these environmental drivers to the spread of the flu in human populations.

Of course, not all of the work can be outsourced to orbiting observatories. Xiao says that judging the severity of avian flu's spread from satellite imaging required knowing details about the human populations as well—for instance, how likely certain communities were to raise ducks for poultry consumption. "Satellite monitoring has a capacity to provide consistent observation," Xiao says. "On the other hand, the in situ observations are still very, very important, so the key is to combine those together. That is a real challenge."

concentrations spanning more than 10 orders of magnitude.

Some companies have simplified the problem by avoiding blood altogether. LabCorp recently commercialized a biomarker test that analyzes colon cells in stool for the chemical signatures indicative of colorectal cancer. "The stool is in intimate contact with the lining of the colon, so it becomes much more highly populated with these rare molecules than would get into the bloodstream from colon cancer," says Barry Berger, chief medical officer of Exact Sciences, a Madison, Wis.–based biotechnology company that developed the test technology.

In time, scientists are confident that they will eventually crack the more difficult problem of finding distinct disease signatures in the noisy data. "The evolutionary process, being complex and unknown, does not always give us an easy route," Berger notes, "but it definitely gives us lots of opportunities."

HEALTH AND MEDICINE

MORE IDEAS TO WATCH

BY MELINDA WENNER

QUICK CLOTS

Emergency technicians could prevent up to 35 percent of prehospital trauma deaths if they had better and cheaper ways to prevent blood loss. Now a University of Maryland–affiliated start-up called Trauma Solutions has developed a synthetic hydrogel that can clot blood by prompting the body to make fibrin, a protein that seals wounds and stops bleeding. Future iterations could simultaneously release such medicines as antibiotics and painkillers. Each application will cost about $5, compared with some natural blood-clotting substances that cost upward of $500.

LAB-ON-A-STAMP

Liver damage is a major side effect of HIV/AIDS and tuberculosis drugs, yet few developing countries have enough trained scientists or equipment to monitor it. Nonprofit Cambridge, Mass.–based Diagnostics For All has developed an inexpensive fingernail-size device made almost entirely of paper that monitors liver damage using a single drop of blood. Channels in the paper guide blood to regions that change color depending on the levels of two damage-related liver enzymes.

BACTERIAL TOOTHPASTE

Streptococcus mutans bacteria in the mouth decay teeth by converting sugars into enamel-eroding lactic acid. Florida-based Oragenics has genetically engineered a new strain of bacteria that converts sugars to trace amounts of alcohol instead. Because the new strain permanently displaces natural *S. mutans*, the therapy, which is currently in clinical trials, will be available as a one-time prescription that will protect teeth for life.

➥ MORE TO EXPLORE

ENERGY

The Borrower's Guide to Financing Solar Energy Systems: A Federal Overview. Department of Energy, National Renewable Energy Laboratory. **http://tinyurl.com/borrowedsolar**

TRANSPORTATION

Plug-In America: **www.pluginamerica.org**

ENVIRONMENT

The Marine Conservation Biology Institute: **www.mcbi.org**

ELECTRONICS AND ROBOTICS

Building a Sensor-Rich World. Special issue of *IEEE Pervasive Computing*, Vol. 6, No. 2; April-June 2007.

HEALTH AND MEDICINE

Cancer Biomarkers—An Invitation to the Table. William S. Dalton and Stephen H. Friend in *Science*, Vol. 312, pages 1165–1168; May 26, 2006.

EXPANDING the Limits of Life

Analyses of a recently discovered type of hot vent ecosystem in the seafloor suggest new possibilities for how life evolved **By Alexander S. Bradley**

Few places on Earth's continents remain to be explored, and it is unlikely that many new natural wonders await discovery in some forgotten corner. But below the ocean surface is a different story. We know more about the facade of Mars than about the 75 percent of our own planet's surface that lies underwater. Untold surprises await us there.

One such revelation occurred in December 2000. An expedition mapping a submerged mountain known as the Atlantis Massif, midway between Bermuda and the Canary Islands and half a mile under the surface of the North Atlantic, came across a pillar of white rock as tall as a 20-story building rising from the seafloor. Using the remotely operated ArgoII vehicle and the manned submersible *Alvin*, scientists surveyed and sampled the mysterious formation. Although time constraints limited their investigation to a single *Alvin* dive, the researchers were able to collect enough information to determine that the white pillar was just one of several such structures in the area that were emitting heated seawater. They had discovered a field of undersea hot springs they named the Lost City Hydrothermal Field. It was unlike anything seen before, including the now famous black smokers.

The initial report describing the discovery, published in the journal *Nature* in July 2001, sent waves of excitement throughout the scientific community. Lead author University of Washington geologist Deborah S. Kelley and her colleagues raised many fundamental questions. How did this hydrothermal field form? What kinds of organisms live there, and how do they survive? In 2003 Kelley led a full-scale, six-week expedition to Lost City to find out. After years of painstakingly analyzing the samples collected during that mission, specialists are now beginning to compose fascinating answers.

The findings from Lost City have prompted reconsideration of long-standing notions about the chemistry that may have set the stage for the emergence of life on Earth. The results have expanded researchers' ideas about where life beyond the Blue Planet might exist—and challenged established ideas about how to search for it.

Strange Chemistry

Scientists have known about undersea hydrothermal vents since the 1970s. The black smoker systems are the most familiar; they occur at mid-ocean ridges—those strings of volcanoes overlying spots where tectonic plates are pulling away from one another. The water at these vents can reach temperatures above 400 degrees Celsius because of their proximity to molten rock. With a pH similar to lemon juice, the scorching water leaches sulfide, iron, copper and zinc as it filters

KEY CONCEPTS

- In 2000 researchers discovered a new kind of undersea hydrothermal vent system that they named the Lost City.
- Over the past few years analyses of samples collected from the site have revealed the site's unique chemistry, as well as the microorganisms that exploit it.
- The findings hint that life may have originated in an environment like the Lost City.

—The Editors

LOST CITY hydrothermal vent ecosystem appears barren but hosts a wealth of microbes, many of which flourish independent of energy from sunlight.

through the volcanic rocks below the seafloor. As this hot, acidic fluid then rises back to the surface of the seafloor, it is discharged through the vents into cold seawater, where the dissolved metal sulfides quickly cool and precipitate out of the fluid, producing a cloudy mix that looks like billowing black smoke. These metal sulfides accumulate into ever taller chimneys atop the vents. Despite their hostile chemistry, the areas surrounding these vents teem with exotic animals, such as giant, red-tipped *Riftia* tube worms, which lack both mouths and guts but thrive by a symbiotic association with internal bacteria that consume poisonous hydrogen sulfide gas emanating from the vents.

Compared with the savage black smoker environment, the Lost City vents are eerily tranquil. Located about 15 kilometers to the west of the tectonic plate boundary at the Mid-Atlantic Ridge, this vent field atop the Atlantis Massif is too distant for rising magma to heat the fluids to the blistering temperatures found at black smokers. Instead the water is heated by circulation through the merely warm rock below, and the highest measured temperature is only 90 degrees C. Neither are the Lost City fluids acidic. They

are alkaline, with a pH between 9 and 11—similar to milk of magnesia or household ammonia solution. Because these waters cannot readily dissolve high concentrations of metals such as iron and zinc, Lost City does not produce the metal sulfide plumes that characterize black smokers. Rather Lost City vent waters are rich in calcium, which on mixing with seawater produces calcium carbonate (limestone). This limestone forms giant white chimneys, the largest of which towers nearly 60 meters above the seafloor—significantly taller than the loftiest black smoker chimney.

The strange chemistry at Lost City derives from its unique geologic setting, which is rooted in the structure of the planet itself. Picture Earth as a peach. The skin represents the crust, the flesh is equivalent to the underlying solid mantle layer, and the pit stands in for the hot iron core. At the Mid-Atlantic Ridge, the crust is being slowly pulled apart as North America and Africa move away from each other at a sluggish 25 millimeters a year. The separation of the crust has exposed parts of Earth's mantle at the seafloor, and uplift of this exposed mantle has formed the Atlantis Massif.

The mantle consists mainly of a rock called peridotite, which turns out to be the key to the Lost City's distinctive chemistry. When peridotite comes into contact with water, it undergoes a chemical reaction called serpentinization. As seawater seeps into the depths of the massif, the peridotite is altered to serpentinite, and the percolating waters become more alkaline as a result of that reaction. By the time fluids reemerge and mix with the ocean waters, they are loaded with calcium released during serpentinization. Most significant of all, they are now highly reduced, meaning that all the oxygen has been stripped from the water and replaced with energy-rich gases such as hydrogen, methane and sulfide. The concentrations of hydrogen, in particular, are among the highest ever encountered in a natural environment. And that is where things begin to get really interesting.

In the Beginning

Hydrogen is full of energy as a consequence of its ability to transfer electrons to other compounds, such as oxygen, releasing energy in the process. Compounds that can readily donate electrons to other compounds are described somewhat confusingly as "chemically reduced." Scientists have long suspected that reduced gases played an important role in the origin of life on Earth. In the 1920s Russian biochemist Alexander Oparin and British evolutionary biologist J.B.S. Haldane each suggested that the primitive atmosphere of Earth might have been very rich in reduced gases such as methane, ammonia and hydrogen. If the atmosphere had high concentrations of these gases, they proposed, the chemical ingredients required for life might have formed spontaneously.

The idea gained credibility several decades later with the famous 1953 experiment by chemists Stanley Miller and Harold Urey of the University of Chicago. By heating and discharging sparks through a mixture of reduced gases, Miller and Urey were able to create a range of organic compounds (most compounds containing carbon and hydrogen), including amino acids, the building blocks of proteins used by all life-forms on Earth.

In the years after the Miller-Urey experiment, however, geologists concluded that the early atmosphere was not nearly as reduced as the duo had assumed. The conditions that formed amino acids and other organic compounds in their experiment, these scientists said, probably never existed in the atmosphere.

But reduced gases abound in the Lost City hydrothermal vents. Could it be that billions of years ago, vents similar to these had the right

[FINDINGS]

CRADLE OF LIFE?

The Lost City vents sit on an underwater peak known as the Atlantis Massif, 15 kilometers west of the tectonic plate boundary at the Mid-Atlantic Ridge. Studies of the vents have revealed how their chimneys formed and suggest that the chemistry there is the sort that could have given rise to the earliest life on Earth.

The massif consists mostly of a rock called peridotite. As seawater filters through fractures in the massif, it reacts with the peridotite, transforming it into serpentinite. This serpentinization drives several processes that are important to the chemistry of Lost City. One, it gives the warm, percolating water an alkaline pH and releases calcium into it. As the water emerges from the vents and mixes with seawater, calcium carbonate forms and precipitates atop the vents, forming white chimneys. Also, the reaction loads the vent fluids with energy-rich gases, including hydrogen, which enable microbes such as methanogens to thrive on and within the chimney walls independent of energy from the sun. Finally, the serpentinization produces chemical conditions that allow the synthesis of organic compounds from inorganic ones—a prerequisite to the evolution of life.

LOST CITY ...

Both Lost City and black smokers are underwater hot springs. But beyond that, they differ considerably. Below are some of the attributes that characterize Lost City.

- Located 15 kilometers west of the Mid-Atlantic Ridge volcanoes
- Water temperatures up to 90 degrees Celsius
- pH is highly alkaline
- Calcium carbonate forms white chimneys
- Some life-forms operate independent of energy from the sun

DON FOLEY (*map and cutaway*); SOURCE FOR MAP: UNIVERSITY OF WASHINGTON; COURTESY OF UNIVERSITY OF WASHINGTON, IFE, URI-IAO, LOST CITY SCIENCE PARTY AND NOAA (*vent*)

ILLUSTRATION COURTESY OF D. S. KELLEY AND CENTER FOR ENVIRONMENTAL VISUALIZATION, UNIVERSITY OF WASHINGTON; COURTESY OF G. FRUH-GREEN *NOAA (serpentinite)*; MICHAEL SZOENYI *Photo Researchers, Inc. (peridotite)*; B. J. MURTON *Southampton Oceanography Center/Photo Researchers, Inc. (vent)*

... VS. BLACK SMOKERS

The proximity of black smokers to rising magma contributes significantly to the traits that distinguish these vents from the ones at Lost City.

- Located at the Mid-Atlantic Ridge volcanoes
- Water temperatures up to 400 degrees Celsius
- pH is highly acidic
- Sulfide minerals produce black smoke and form chimneys
- Life-forms are indirectly dependent on energy from the sun

conditions to produce the types of organic compounds required for life? Some geochemists investigating this question think so. A number of studies conducted over the past decade have suggested that the chemical reactions that occur during serpentinization are ideal for the production of organic compounds from carbon dioxide. Hydrothermal systems akin to Lost City might have been primitive factories that churned out methane, simple organic acids and perhaps even more complex fatty acids—essential components of the cellular membranes of all organisms. And the vents might have been able to generate these organic compounds without the assistance of living organisms.

Lost City is a natural laboratory for testing these ideas. In 2008 chemist Giora Proskurowski of the Woods Hole Oceanographic Institution and his colleagues published a paper in the journal *Science* demonstrating that the hydrothermal fluids at Lost City do indeed contain small organic compounds such as methane, ethane and propane. Other work suggests that the reactions at Lost City also produce small organic acids such as formate and acetate. Together these findings confirm that the reduced conditions at the Lost City vents could support the types of chemical reactions necessary to create organic compounds from inorganic compounds—a simple but critical step in prebiotic chemistry.

This new work establishes that some hydrothermal vent environments are able to produce at least simple organic compounds, possible ingredients for life. But Lost City is not a perfect setting for testing such ideas, because the carbonate towers are not sterile chemical reactors. In fact, they teem with microbial life, which raises the possibility that these microbes could be contributing to the formation of organic compounds in the vent fluids. To resolve this puzzle, we must take a closer look at the microbes themselves.

No Sun Needed

Many microorganisms have evolved the ability to consume the abundant energy contained in hydrogen. Methanogens constitute one such group. As their name suggests, methanogens generate methane: the natural gas that many of us use to heat our homes and cook our food. It turns out that up to one third of the microbes at Lost City are methanogens belonging to the family Methanosarcinales. Their presence is not surprising given the abundance of hydrogen in the vent fluids. What is remarkable is that the Lost City methanogens operate independently of the sun.

Virtually all life on Earth depends on solar energy—be it humans, who rely on photosynthetic organisms for food, or plants and algae

that photosynthesize. Even at black smokers, in the darkest depths of the oceans, life depends on the sun. The microbes that support the growth of the giant tube worms, for example, require both sulfide and oxygen. The ultimate source of the oxygen is photosynthetic organisms far above. In contrast, all that the Lost City methanogens need to survive is carbon dioxide, along with liquid water and peridotite, which react to form the raw ingredients they require.

Investigators have found that both geochemical reactions stemming from serpentinization and the activity of biological methanogens contribute methane to the Lost City ecosystem. This simultaneous generation of methane may not be a coincidence. In a series of studies over the past few years, biochemist William Martin of Heinrich-Heine University in Germany and geochemist Michael Russell of the NASA Jet Propulsion Laboratory in Pasadena examined the precise chemical steps required to produce methane abiotically, that is, without living organisms in environments such as that in Lost City. They found that each step is replicated in the biological pathways of organisms that generate methane. From this work, Martin and Russell proposed that on the early Earth, sites like Lost City produced methane geochemically and that primordial life-forms may have simply co-opted each of the chemical steps for themselves, leading to what might have been the origin of the first biochemical pathway.

Martin and Russell are not the first scientists to suggest that life might have arisen at a hydrothermal vent. That idea has been around for a number of years. Support for it comes not only from the advantageous chemistry at hydrothermal systems but also from the evolutionary record found in the genetic material of all living organisms.

The study of ribosomes—biological machines that the cell uses to translate the information encoded in nucleic acids (DNA and RNA) into proteins—has proved especially enlightening in this regard. The ribosomes are themselves built of both RNA and protein. By comparing the sequences of the ribosomal RNA building blocks, or nucleotides, scientists have constructed a family tree that shows the relationships of all life on Earth. Many of the organisms that reside on branches near the root of the tree consume hydrogen and inhabit high-temperature hot springs, either on land or on the seafloor, indicating that the last universal ancestor of all life on Earth may also have inhabited a hot spring, possibly in an environment resembling that of the Lost City Hydrothermal Field.

Geologists have reason to suspect that ecosystems like that of Lost City may have once been relatively common. Peridotite is among the most prevalent types of rock in the solar system. On Earth, it makes up the bulk of the upper mantle. Although newly formed peridotite is rarely found on the terrestrial surface today, it was abundant three billion to four billion years ago. Back then, the planet was much hotter, and increased volcanism transported more of the molten mantle to the surface. In fact, peridotite probably made up most of the rock on the seafloor of the early Earth. This rock would have reacted with water then just as it does now. Warm, alkaline settings akin to Lost City may have thus nurtured the first life-forms. Fiery acidic conditions similar to those found at black smokers, in contrast, would probably have been too hostile to foster the emergence of life.

The findings from Lost City also bolster hypotheses about where else in our solar system life might exist or have existed in the past. Any planet or moon containing both peridotite and liquid water—the ingredients necessary for serpentini-

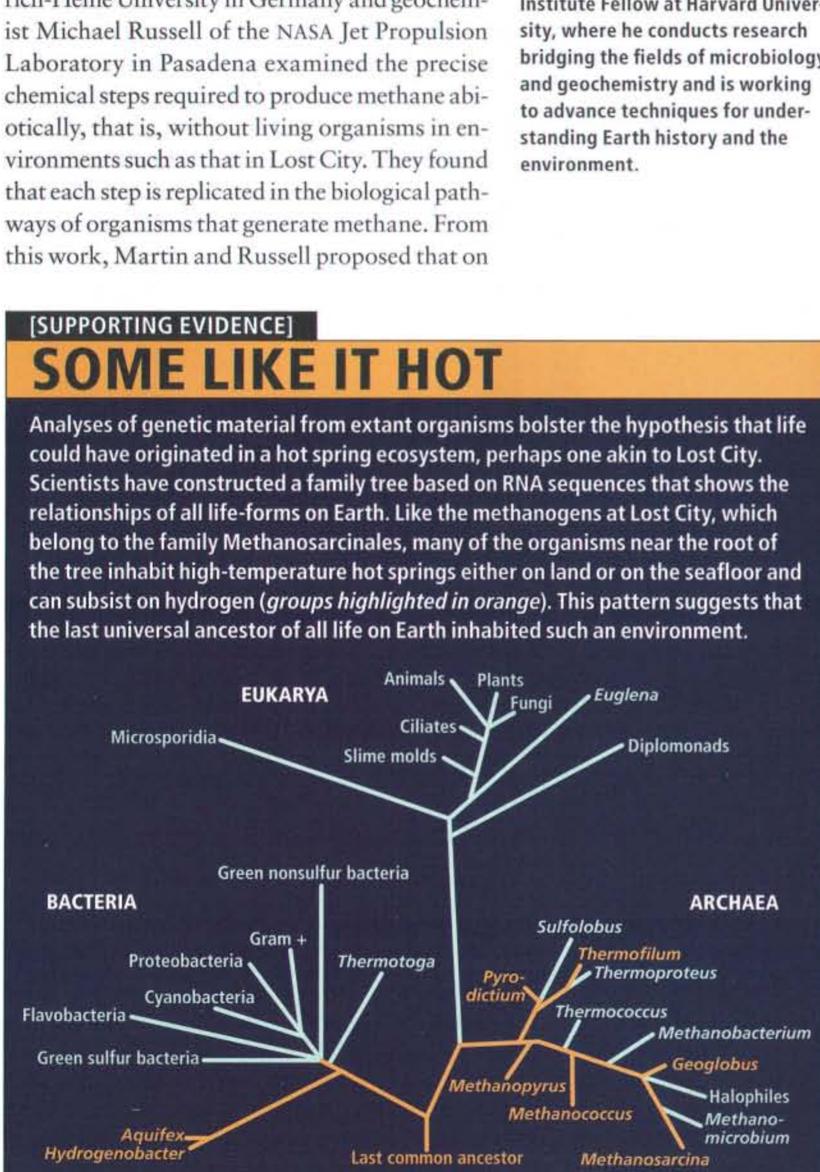
[THE AUTHOR]

Alexander S. Bradley completed his Ph.D. in geochemistry at the Massachusetts Institute of Technology in 2008. His dissertation research focused on examining organic compounds in the hydrothermal systems at Lost City and in Yellowstone National Park. Bradley is currently an Agouron Institute Fellow at Harvard University, where he conducts research bridging the fields of microbiology and geochemistry and is working to advance techniques for understanding Earth history and the environment.

[SUPPORTING EVIDENCE]

SOME LIKE IT HOT

Analyses of genetic material from extant organisms bolster the hypothesis that life could have originated in a hot spring ecosystem, perhaps one akin to Lost City. Scientists have constructed a family tree based on RNA sequences that shows the relationships of all life-forms on Earth. Like the methanogens at Lost City, which belong to the family Methanosarcinales, many of the organisms near the root of the tree inhabit high-temperature hot springs either on land or on the seafloor and can subsist on hydrogen (*groups highlighted in orange*). This pattern suggests that the last universal ancestor of all life on Earth inhabited such an environment.



COURTESY OF MARIANNA RUZINOVA (*Bradley*); MELISSA THOMAS (*tree diagram*)

zation—could conceivably support life-forms analogous to microbes at Lost City. Evidence of these components is strongest on Mars and on Jupiter's moon Europa. Indeed, researchers have already detected methane in the modern Martian atmosphere. Whether it comes from microbes or chemical reactions in the planet's rocks—or both—remains uncertain, however.

Sourcing Methane

Making that determination may turn out to be harder than scientists had envisioned. Most of the organisms on the tree of life are microbes. Although we can study the DNA and RNA sequences of such organisms, finding a fossil record of small creatures with ambiguous shapes is difficult. To that end, in the past few decades researchers have developed techniques that permit investigation of the evolutionary history of microbes by combing the geologic record not for physical fossils but for chemical ones. Chemical fossils are molecules that can be traced to living organisms and can be preserved as fossils in rocks over millions or even billions of years. Most chemical fossils are derived from the lipids that make up cell membranes. Although lipids do not hold as much information as DNA or a physical fossil does, they are reliable indicators of life and can carry structures diagnostic of the organisms that produced them.

Moreover, the carbon that constitutes the lipids is itself informative, because it contains a marker that reveals how an organism extracted carbon from its environment. That marker is carbon 13, a relatively rare form of the element that does not degrade over time. The carbon in most organisms includes between 1 and 3.5 percent less carbon 13 than does the carbon in the carbon dioxide dissolved in seawater. Scientists have thus assumed that carbon in ancient rocks that is depleted by this amount derived from living organisms. And as a corollary to that rule, carbon from ancient rocks that is not depleted comes from abiotic processes.

But Lost City puts the lie to that notion. My work with a team of scientists at the Massachusetts Institute of Technology and at Woods Hole has shown that some of the most abundant lipids found in the carbonates at Lost City are from methanogens. Yet these lipids exhibit no carbon 13 depletion whatsoever. Instead their carbon 13 contents are what one would expect from material that did not derive from living organisms.

How can this be? The use of carbon 13 as a tracer of life rests on the assumption that more carbon dioxide is available in the environment than can be used. As long as there is a surplus of carbon dioxide, organisms can incorporate lighter carbon 12 molecules, which they prefer, and discriminate against the heavier carbon 13. But if carbon dioxide were somehow scarce, organisms would scrounge for every available carbon molecule that they could get, be it the lighter variety or the heavier one. And if that were to occur, the relative abundance of carbon 13 in the organisms would be no different from that in the environment. The chemical tracer of life would be invisible.

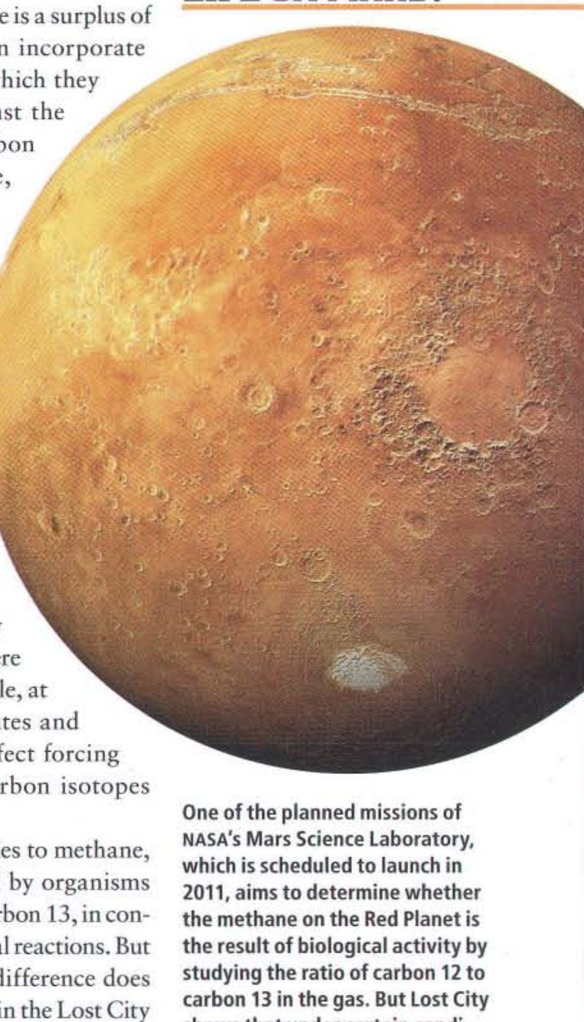
This process is exactly what is happening at the Lost City vents. Unlike nearly every other environment on Earth, where carbon dioxide is always available, at Lost City hydrogen predominates and carbon dioxide is scarce, in effect forcing organisms there to extract carbon isotopes indiscriminately.

The invisibility problem applies to methane, too. Usually methane produced by organisms shows an extreme depletion in carbon 13, in contrast to methane from geochemical reactions. But in serpentinizing systems, this difference does not always appear. The methane in the Lost City vent waters lacks the telltale carbon 13 depletion. Researchers know from observation that this methane is a mixture of geologic and biological products. Carbon isotopes alone are incapable of making the distinction, though.

If life has evolved elsewhere in our solar system, the best bet may be that it consists of microbial methanogens living in sites where rock is being serpentinized. We know that methane is somehow being produced on Mars. NASA plans to launch the Mars Science Laboratory in 2011, and one of its missions will be to determine the carbon isotope ratio of that methane. A strong depletion in carbon 13 would be an indication that organisms inhabit the Red Planet.

Yet Lost City demonstrates that failure to find that signal can hardly be considered evidence of absence. Indeed, the discovery of microbes thriving in this previously unknown type of ecosystem provides yet more reason to expect that scientists will one day find signs of life beyond Earth. ■

LIFE ON MARS?



One of the planned missions of NASA's Mars Science Laboratory, which is scheduled to launch in 2011, aims to determine whether the methane on the Red Planet is the result of biological activity by studying the ratio of carbon 12 to carbon 13 in the gas. But Lost City shows that under certain conditions the carbon isotope ratio cannot distinguish between geologic and biological sources. Hence, a negative signal from the carbon isotope ratio would not rule out the possibility that life exists there.

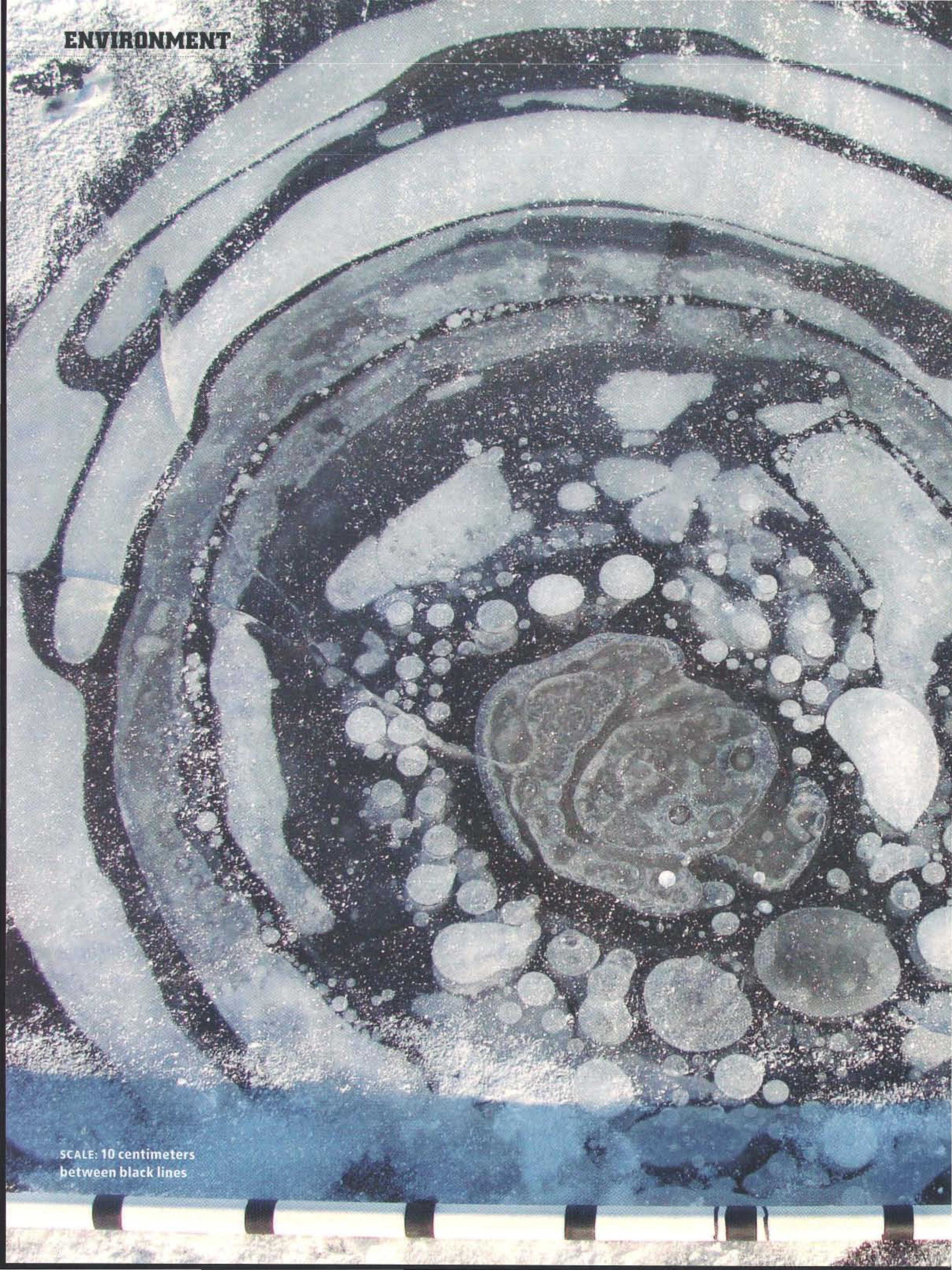
DETLEV VAN RAVENSWAAY *Photo Researchers, Inc.*

➡ MORE TO EXPLORE

Dawn in the Deep: The Bizarre World of Hydrothermal Vents. Richard A. Lutz in *National Geographic,* Vol. 203, No. 2, pages 92–103; February 2003.

The Mystery of Methane on Mars and Titan. Sushil K. Atreya in *Scientific American,* Vol. 296, No. 5, pages 24–43; May 2007.

Lost City Expedition Web site: **www.lostcity.washington.edu**



SCALE: 10 centimeters between black lines

COURTESY OF KATEY WALTER ANTHONY

Methane: A MENACE SURFACES

Arctic permafrost is already thawing, creating lakes that emit methane. The heat-trapping gas could dramatically accelerate global warming. How big is the threat? What can be done?

BY KATEY WALTER ANTHONY

Touchdown on the gravel runway at Cherskii in remote northeastern Siberia sent the steel toe of a rubber boot into my buttocks. The shoe had sprung free from gear stuffed between me and my three colleagues packed into a tiny prop plane. This was the last leg of my research team's five-day journey from the University of Alaska Fairbanks across Russia to the Northeast Science Station in the land of a million lakes, which we were revisiting as part of our ongoing efforts to monitor a stirring giant that could greatly speed up global warming.

These expeditions help us to understand how much of the perennially frozen ground, known as permafrost, in Siberia and across the Arctic is thawing, or close to thawing, and how much methane the process could generate. The question grips us—and many scientists and policy makers—because methane is a potent greenhouse gas, packing 25 times more heating power, molecule for molecule, than carbon dioxide. If the permafrost thaws rapidly because of global warming worldwide, the planet could get hot-

KEY CONCEPTS

- Methane bubbling up into the atmosphere from thawing permafrost that underlies numerous Arctic lakes appears to be hastening global warming.
- New estimates indicate that by 2100 thawing permafrost could boost emissions of the potent greenhouse gas 20 to 40 percent beyond what would be produced by all natural and man-made sources.
- The only realistic way to slow the thaw is for humankind to limit climate warming by reducing our carbon dioxide emissions. *—The Editors*

ter more quickly than most models now predict. Our data, combined with complementary analyses by others, are revealing troubling trends.

Leaving the Freezer Door Open

Changes in permafrost are so worrisome because the frozen ground, which covers 20 percent of the earth's land surface, stores roughly 950 billion tons of carbon in the top several tens of meters. (More permafrost can extend downward hundreds of meters.) This carbon, in the form of dead plant and animal remains, has accumulated over tens of thousands of years. As long as it stays frozen beneath and between the many lakes, it is safely sequestered from the air.

But when permafrost thaws, the carbon previously locked away is made available to microbes, which rapidly degrade it, producing gases. The same process happens if a freezer door is left open; given long enough, food thaws and begins to rot. Oxygen stimulates bacteria and fungi to aerobically decompose organic matter, producing carbon dioxide. But oxygen is depleted in soil that is waterlogged, such as in lake-bottom sediments; in these conditions, anaerobic decomposition occurs, which releases methane (in addition to some carbon dioxide). Under lakes, the methane gas molecules form bubbles that escape up through the water column, burst at the surface and enter the atmosphere.

Anaerobic decomposition is the primary source of methane in the Arctic. Melting ice in permafrost causes the ground surface to subside. Runoff water readily fills the depressions, creating many small, newly formed lakes, which begin to spew vast quantities of methane as the permafrost that now lines their bottom thaws much more extensively. Scars left behind reveal that this process has been going on for the past 10,000 years, since the earth entered the most recent interglacial warm period. Satellite recordings made during recent decades suggest, however, that permafrost thaw may be accelerating.

Those recordings are consistent with observations made at numerous field-monitoring sites across Alaska and Siberia maintained by my Fairbanks colleague Vladimir E. Romanovsky and others. Romanovsky notes that permafrost temperature at the sites has been rising since the early 1970s. Based on those measurements, he calculates that one third to one half of permafrost in Alaska is now within one degree to one and a half degrees Celsius of thawing; in some places worldwide, it is already crossing that critical zero degrees C threshold.

Ongoing observations, made by my research team during trips to Cherskii and numerous other sites and by our colleagues, reinforce the sense that thawing is accelerating and indicate that the emissions could be much greater than anticipated. My group's latest estimates are that under current warming rates, by 2100 permafrost thawing could boost methane emissions far beyond what would be produced by all other natural and man-made sources. The added greenhouse gas, along with the extra carbon dioxide that exposed, thawing ground would release, together could raise the mean annual temperature of the earth by an additional 0.32 degree C, according to Vladimir Alexeev, also at Fairbanks.

That increase may sound minor, but it is not; it would contribute significantly to global-warming-induced upset of weather patterns, sea level, agriculture and disease dispersal. If deeper sources of methane were to escape—such as that stored in material known as methane hydrates [*see box on page 50*]—the temperature rise could be as high as several degrees. Therefore, humankind has more reason than ever to aggressively slow the current rate of warming so that we do not push large regions of the Arctic over the threshold.

THREATENED BY THE NUMBERS

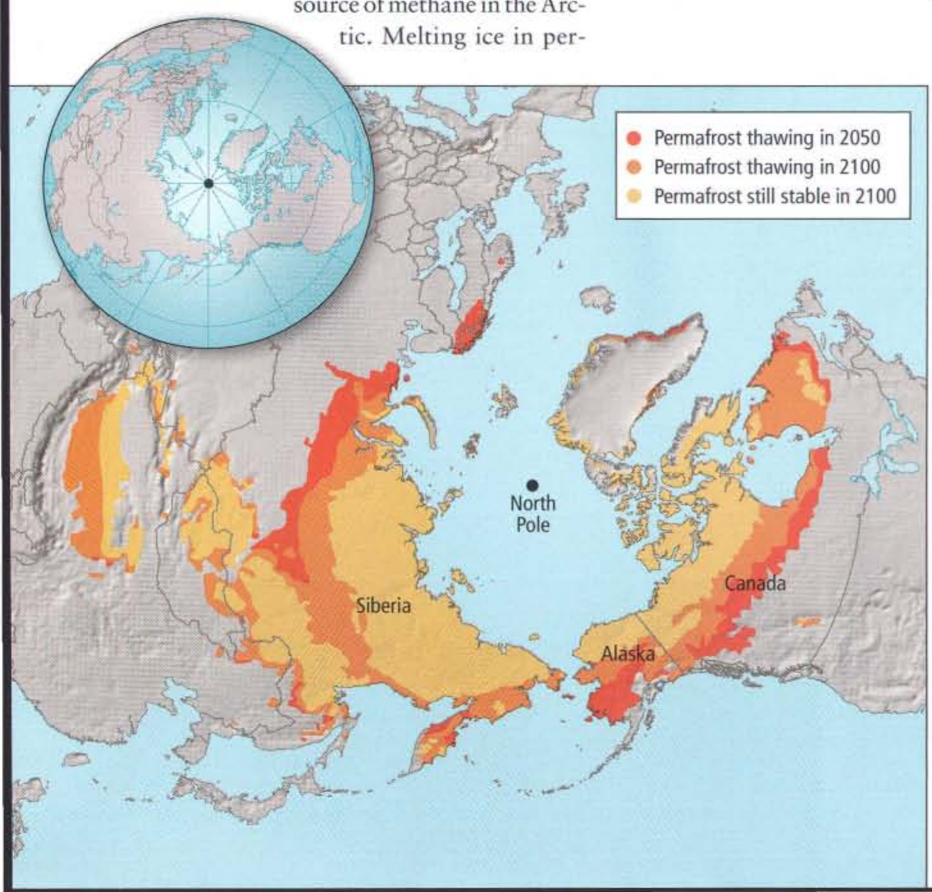
Permafrost covers **20%** of the earth's land surface.

One third to one half of permafrost, a rich source of methane, is now within **1.0° C to 1.5° C** of thawing.

At predicted rates of thaw, by 2100 permafrost will boost methane released into the atmosphere **20% to 40%** beyond what would be produced by all other natural and man-made sources.

Methane in the atmosphere has **25 times** the heating power of carbon dioxide.

As a result, the earth's mean annual temperature could rise by an additional **0.32° C**, further upsetting weather patterns and sea level.



◄ **NORTHERN EXPOSURE: Vast swaths of permafrost will thaw by 2050 and 2100 if global warming continues unabated, releasing large quantities of methane that will worsen warming.**

MAPPING SPECIALISTS

The Mother Lode in Siberia

Probing regions such as Cherskii is key to verifying—or revising—our estimations. Walking along a Siberian riverbank with my colleague from the Northeast Science Station, Sergei A. Zimov, I am careful where I stop. The skin of the earth is only a half meter thick, made up largely of muddy, mossy peat that sits loosely atop ice that is 40 to 80 meters deep. The stunted trees are slanted at various angles in this "drunken forest" because they cannot send roots into the frozen ground, and cycles of summer thaws generate large heaves. Behind me, one drunken tree crashes to the ground; through the torn blanket of forest floor we see the shiny black surface of solid ice and catch the musty scent of decomposing organic matter. It is also hard not to stub one's toe on the plethora of scattered bones: woolly rhinoceros, mammoth, Pleistocene lion, bear and horse.

To Zimov, this region is a goldmine—and not because of the tusks and skulls of extinct fauna. In 1989, spurred by an interest in the amount of carbon locked in the ground, he led a group of young scientists that set up the isolated Northeast Science Station to monitor permafrost in tundra and taiga year-round. The researchers traveled the great Russian rivers in small skiffs and scaled cliffs of permafrost without ropes to measure carbon content, the harbinger of methane release. With army tanks and bulldozers, they simulated disturbances that remove surface soil in the way that severe wildfires do. Their experiments proved the size and importance of the permafrost carbon pool to the world.

But why did Zimov—and my group later—concentrate studies here, in a region known previously only for its Soviet gulags? Because not all permafrost is the same. Any ground where the mean annual temperature is below zero degrees C for at least two consecutive years is classified as permafrost, whether ice is present or not. This vast part of Siberia contains a distinct type of permafrost called yedoma, rich in ice and carbon—both central to the methane story. Massive wedges of ice 10 to 80 meters high and smaller lenses constitute up to 90 percent of the ground volume; the remainder is columns of organic-rich soil, a cornucopia of the remains of Pleistocene mammals and the grasses they once ate.

Yedoma formed over roughly 1.8 million square kilometers in Siberia and in a few pockets of North America during the end of the last Ice Age. The organic matter froze in place before microbes could decompose it. A huge storehouse of food was being locked away until conditions would change, leaving the freezer door open.

A warmer climate recently has helped melt the yedoma ice, creating lakes. Vegetation collapses into the edges as the ground thaws and subsides, a process known as thermokarst. Today lakes cover up to 30 percent of Siberia. Further melting makes them larger and deeper, coalescing into broad methane-producing water bodies.

Blown Away by Bubbles

During the 1990s researchers at the Northeast Science Station observed that methane was bubbling out of the bottoms of lakes year-round but they did not know how important the lakes might be globally. Hence, my rough landing by

▲ **HOT ON THE TRAIL: Leading an effort to measure how much methane is escaping into the atmosphere worldwide, the author (*in blue jacket*) and graduate student Dragos Vas collect gas bubbling up to the ice covering a lake in Alaska's interior. Like natural gas, methane is highly flammable.**

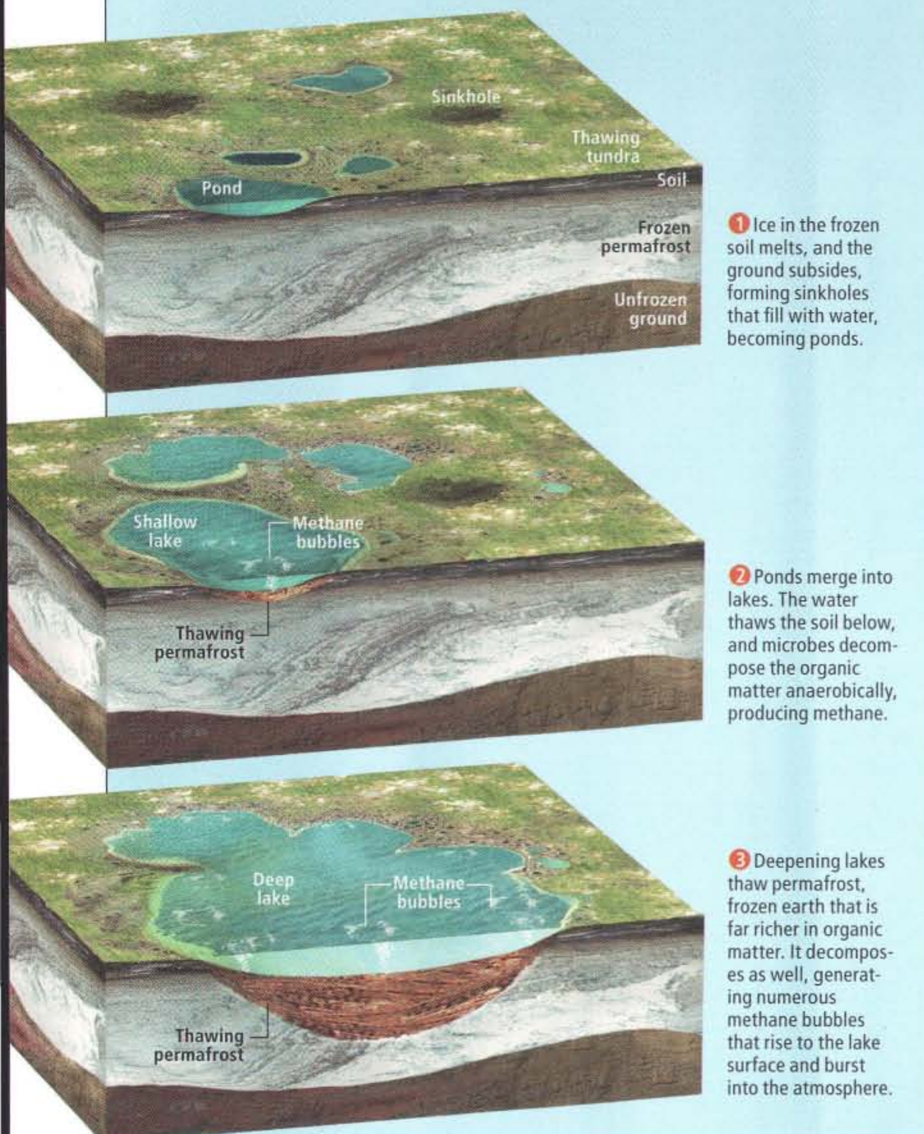
[THE AUTHOR]

Katey Walter Anthony, who previously published as Katey M. Walter, is a research professor at the University of Alaska Fairbanks Water and Environmental Research Center. She splits her time between field sites in Siberia and Alaska, studying methane and carbon dioxide release from lakes and thawing permafrost.

[HOW METHANE IS PRODUCED]

BURSTING BUBBLES

In the cold Arctic environment, dead plant and animal matter lies frozen in ancient permafrost below a thin layer of modern soil. But as the atmosphere warms, the ground thaws. That is when methane production begins.



plane in Cherskii this past August, for my ninth expedition of wading into voraciously expanding thermokarst lakes, to measure changes in permafrost and the release of methane.

My quest had begun as a Ph.D. research project in 2000. At the time, scientists knew that levels of methane—the third most abundant greenhouse gas in the atmosphere after carbon dioxide and water vapor—were rising. The amount and the rate of increased emissions were unprecedented during the previous 650,000 years. Evidence indicated that in bygone eras the methane concentration in the atmosphere fluctuated by 50 percent in association with natural climate variations over thousands of years. But that change was slim by comparison with the nearly 160 percent increase that had occurred since the mid-1700s, rising from 700 parts per billion (ppb) before the industrial revolution to almost 1,800 ppb when I started my project.

Scientists also knew that agriculture, industry, landfills and other human activities were clearly involved in the recent rise, yet roughly half of the methane entering the atmosphere every year was coming from natural sources. No one, however, had determined what the bulk of those sources were.

From 2001 to 2004 I split my time between my cabin in Fairbanks and working with Zimov and others in Cherskii, living with the few local Russian families. In the attic library above our little, yellow wooden research station I spent long nights cobbling together plastic floats that I could place on the lakes to capture bubbles of methane. I dropped the traps by leaning over the side of abandoned boats that I claimed, and I checked them daily to record the volume of gas collected under their large jellyfishlike skirts. In the beginning I did not capture much methane.

Winter comes early, and one October morning when the black ice was barely thick enough to support my weight I walked out onto the shiny surface and exclaimed, "Aha!" It was as if I was looking at the night sky. Brilliant clusters of white bubbles were trapped in the thin black ice, scattered across the surface, in effect showing me a map of the bubbling point sources, or seeps, in the lake bed below. I stabbed an iron spear into one big white pocket and a wind rushed upward. I struck a match, which ignited a flame that shot up five meters high, knocking me backward, burning my face and singeing my eyebrows. Methane!

All winter I ventured across frozen lakes to set more traps above these seeps. More than once I stepped unknowingly on a bubbling hotspot and plunged into ice-cold water. Methane hotspots in lake beds can emit so much gas that the convection caused by bubbling can prevent all but a thin skin of ice from forming above, leaving brittle openings the size of manhole covers even when the air temperature reaches –50 degrees C in the dark Siberian winter. I caught as much as 25 liters (eight gallons) of methane each day from individual seeps, much more than scientists usually find. I kept maps of the hotspots and tallies of their emissions across numerous

KEVIN HAND *(illustration)*; COURTESY OF GUIDO GROSSE *Geophysical Institute, University of Alaska Fairbanks (opposite page)*

lakes. The strongest bubbling occurred near the margins of lakes where permafrost was most actively thawing. The radiocarbon age of the gas, up to 43,000 years old in some places, pointed to yedoma carbon as the culprit.

From 2002 to 2009 I conducted methane-seep surveys on 60 lakes of different types and sizes in Siberia and Alaska. What scientists were not expecting was that the increase in methane emissions across the study region was disproportional to the increase in lake area over that same region. It was nearly 45 percent greater. It was accelerating.

Extrapolated to lakes across the Arctic, my preliminary estimate indicated that 14 million to 35 million metric tons of methane a year were being released. Evidence from polar ice-core records and radiocarbon dating of ancient drained lake basins has revealed that 10,000 to 11,000 years ago thermokarst lakes contributed substantially to abrupt climate warming—up to 87 percent of the Northern Hemisphere methane that helped to end the Ice Age. This outpouring tells us that under the right conditions, permafrost thaw and methane release can pick up speed, creating a positive feedback loop: Pleistocene-age carbon is released as methane, contributing to atmospheric warming, which triggers more thawing and more methane release. Now man-made warming threatens to once again trigger large feedbacks.

How fast might these feedbacks occur? In 2007 global climate models reported by the Intergovernmental Panel on Climate Change (IPCC) projected the strongest future warming in the high latitudes, with some models predicting a rise of seven to eight degrees C by the end of the 21st century. Based on numerous analyses, my colleagues and I predict that at least 50 billion tons of methane will escape from thermokarst lakes in Siberia as yedoma thaws during the next decades to centuries. This amount is 10 times all the methane currently in the atmosphere.

Fine-tuning the Models

Even with our best efforts, our current estimates beg more sophisticated modeling as well as consideration of potential negative feedbacks, which could serve as breaks on the system. For instance, in Alaska, a record number of thermokarst lakes are draining. Lakes formed in upland areas grow

▲ LAKES are forming across Siberia as warming air thaws formerly frozen ground (*above*). Below, the author (*in red jacket*) and graduate student Louise Farquharson sample exposed permafrost (*gray earth*), which often extends tens of meters below a thin cap of unfrozen soil.

until they hit a slope. Then the water flows downhill, causing erosion and further drainage, sending melted sediment into rivers and eventually the ocean. Drained basins fill in with new vegetation, often becoming wetlands. Although they produce methane when they are unfrozen in summer, their total annual emissions are often less than those of lakes.

It is hard to say whether such potential processes would lessen methane release by a sizable amount or just a few percentage points. Two projects of mine, with my Fairbanks colleague Guido Grosse, Lawrence Plug of Dalhousie University in Nova Scotia, Mary Edwards of the University of Southampton in England and others, began in 2008 to improve the first-order approximations of positive and negative feedbacks. A key step is to produce maps and a classification of thermokarst lakes and carbon cycling for regions of Siberia and Alaska, which we hope to draft by early 2010. The cross-disciplinary research links ecological and emissions measurements, geophysics, remote sensing, laboratory incubation of thawed permafrost soils and lake sediments, and other disciplines. The goal is to inform a quantitative model of methane and carbon dioxide emissions from thermokarst lakes from the Last Glacial Maximum (21,000 years ago) to the present and to forecast climate-warming feedbacks of methane from lakes for the upcoming decades to centuries.

To help predict how future warming could affect thermokarst lakes, Plug and a postdoctoral student working with us, Mark Kessler, are developing two computer models. The first, a single-lake model, will simulate the dynamics of a lake basin. The second, a landscape model, includes hill-slope processes, surface-water movement and landscape-scale permafrost changes. The models will first be validated by comparison with landscapes we are already studying, then against data from sediment cores going back 15,000 years in Siberia and Alaska, and then against other climate simulations from 21,000 years ago. The final step will be to couple the thermokarst-lake models with the vast Hadley Center Coupled Model that describes the circulation of oceans and atmosphere—one of the major models used in IPCC assessment reports. The result, we hope, will be a master program that can fully model the extent and effects of permafrost thaw, allowing us to calculate a future rate of

[FUTURE METHANE SOURCES]

HYDRATES: DEEPER TROUBLE

Permafrost is not the world's only methane concern. Vast quantities of the gas lie trapped in ice cages hundreds of meters down in the ground and below ocean bottoms. If these "methane hydrates" were to somehow melt and release their gas to the atmosphere, they would almost certainly trigger abrupt climate change. Evidence in seafloor sediments suggests that this very event, spurred by rapidly rising ocean temperatures, may have occurred 55 million years ago.

Some Russian scientists claim that more than 1,000 billion tons of methane lie beneath the Siberian shelf—submerged land extending seaward from the coastline that eventually drops to the deep ocean. If even 10 percent escaped—100 billion tons—it would be twice the 50 billion tons we project could be released by permafrost thaw [*see main article*]. Warming of the deep ocean is unlikely in the near future. But high concentrations of methane in shallow waters along the shelf have recently been observed; continuing research there should determine whether the source is hydrates or (more likely) decomposing organic matter in permafrost thawing in the shallow seafloor.

On land, if lake-bed thawing extended like fingers deeper into the earth below, it could conceivably break into hydrate deposits and give them a channel to bubble upward to and through the water and into the atmosphere. My group is collaborating with U.S. Geological Survey scientists Carolyn Ruppel and John Pohlman to evaluate this possibility.

If hydrates prove to be a threat, the effect might be counteracted a bit by extracting the methane as a fuel before it is released. The methane in global hydrates would produce more energy than all the natural gas, oil and coal deposits on earth combined. Very little of it would ever be economically recoverable, however, because it is too dispersed in geologic strata, making exploration and extraction too expensive, even if oil was $100 a barrel. In a few places, mining concentrated hydrates might prove more affordable, and countries such as Japan, South Korea and China, eager to reduce fossil-fuel imports, are investing in technology to possibly extract those deposits. ConocoPhillips and British Petroleum are assessing the commercial feasibility of certain hydrates in the U.S.

Tapping hydrates is controversial. If enough evidence suggested an imminent, uncontrolled release of methane from destabilized hydrates, then capturing the gas instead would help mitigate climate warming. No proof of large hydrate releases exists yet, however, so commercial extraction would simply exasperate fossil-fuel driven climate changes. From a global-warming point of view, we are better off leaving those hydrates deep underground.

—K.W.A.

THE GIANT BELOW ▼

Large, deep deposits of ice and gas known as hydrates could suddenly release vast quantities of methane if breached. Two theoretical pathways might exist. 1 On land, thawing fingers of permafrost could extend downward and break into a deposit, allowing methane to vent upward. 2 Under continental shelves, warming ocean water could thaw the thin permafrost cap, then melt the icy hydrate, allowing methane to bubble up.

KEVIN HAND

methane release and assess how that would drive global temperatures.

More fieldwork, of course, will continue to refine the data going into such models. In 2010, with the help of a hovercraft, we will investigate lakes along nearly 1,000 miles of Siberian rivers and Arctic coast. A huge expedition will also retrieve sediment cores from lakes dating back millennia. Field data, together with remote sensing, will ultimately be used in the Hadley Center program to model climate change drivers from the Last Glacial Maximum to 200 years into the future. Maps of predicted permafrost thaw and methane release should be complete by April 2011.

▲ SOLUTION? A reindeer herder fixes a fence that surrounds a large area of Siberia known as Pleistocene Park. Grazing animals such as Yakutian horses are being introduced there to better establish grasslands that will help keep permafrost frozen.

COURTESY OF SERGEI A. ZIMOV *Northeast Science Station*

Solutions

If, as all indicators suggest, Arctic methane emissions from permafrost are accelerating, a key question becomes: Can anything be done to prevent methane release? One response would be to extract the gas as a relatively clean fuel before it escapes. But harvesting methane from the millions of lakes scattered across vast regions is not economically viable, because the seeps are too diffuse. Small communities that are close to strong seeps might tap the methane as an energy source, however.

Zimov and his son, Nikita, have devised an intriguing plan to help keep the permafrost in Siberia frozen. They are creating a grassland ecosystem maintained by large northern herbivores similar to those that existed in Siberia more than 10,000 years ago. They have introduced horses, moose, bears and wolves to "Pleistocene Park," a 160-square-kilometer scientific reserve in northeastern Siberia. They intend to bring back musk ox and bison, depending on funding, which comes from independent sources, the Russian government and U.S. agencies.

These grazing animals, along with mammoths, maintained a steppe-grassland ecosystem years ago. The bright grassland biome is much more efficient in reflecting incoming solar radiation than the dark boreal forest that has currently replaced it, helping to keep the underlying permafrost frozen. Furthermore, in winter the grazers trample and excavate the snowpack to forage, which allows the bitter cold to more readily chill the permafrost.

One man and his family have taken on a mammoth effort to save the world from climate change by building Pleistocene Park. Yet a global response is needed, in which every person, organization and nation takes responsibility to reduce their carbon footprint. Slowing emissions of carbon dioxide is the only way humankind can avoid amplifying the feedback loop of greater warming causing more permafrost thaw, which causes further warming. We predict that if carbon emissions increase at their current projected rate, northern lakes will release 100 million to 200 million tons of methane a year by 2100, much more than the 14 million to 35 million tons they emit annually today. Total emissions from all sources worldwide is about 550 million tons a year, so permafrost thaw, if it remains unchecked, would add another 20 to 40 percent, driving the additional 0.32 degree C rise in the earth's mean annual temperature noted earlier. The world can ill afford to make climate change that much worse. To reduce atmospheric carbon dioxide and thereby slow permafrost thaw, we all must confront the elephant in the room: people burning fossil fuels. ■

CITIZEN SCIENCE: METHANE IN LAKES NEAR YOU

Do you live near a lake? How much methane does it release? Methane rises from any lake bottom in which organic matter is decomposing, regardless of latitude. Beaver ponds are particularly productive. To find out how you can take part in mapping methane seeps in your own backyard, visit the Pan-Arctic Lake-Ice Methane Monitoring Network (www.alaska.edu/uaf/cem/ine/walter/ongoing_projects.xml). Educators can also get involved through a student program at the same Web site.

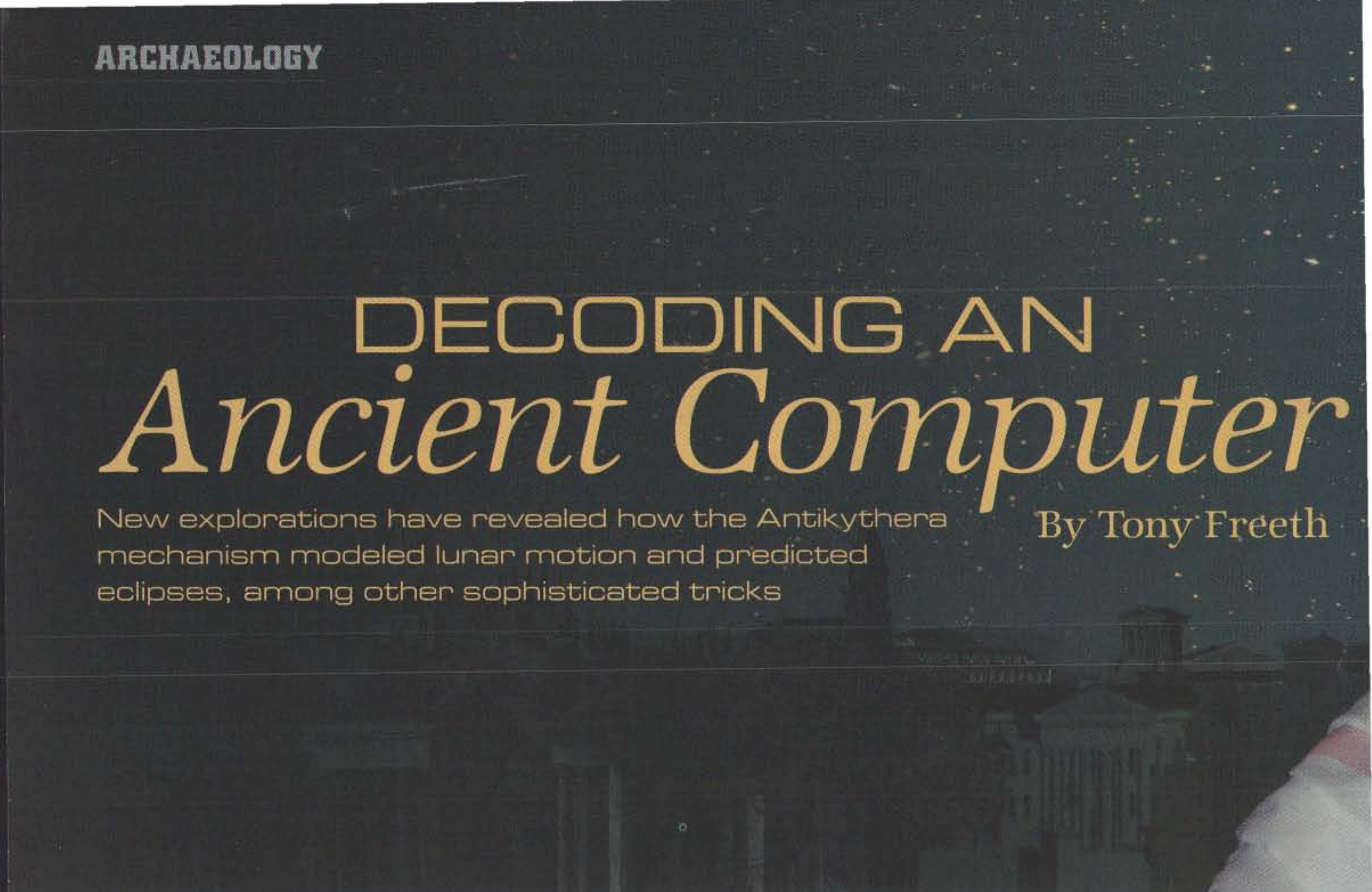
➡ MORE TO EXPLORE

Methane Bubbling from Siberian Thaw Lakes as a Positive Feedback to Climate Warming. K. M. Walter et al. in *Nature*, Vol. 443, pages 71–75; September 7, 2006.

Thermokarst Lakes as a Source of Atmospheric CH_4 during the Last Deglaciation. K. M. Walter et al. in *Science*, Vol. 318, pages 633–636; October 26, 2007.

Assessing the Spatial and Temporal Dynamics of Thermokarst, Methane Emissions, and Related Carbon Cycling in Siberia and Alaska. G. Grosse, K. Walter and V. E. Romanovsky. NASA Carbon Cycle Sciences Project, April 2008–March 2011.

Understanding the Impacts of Icy Permafrost Degradation and Thermokarst-Lake Dynamics in the Arctic on Carbon Cycling, CO_2 and CH_4 Emissions, and Feedbacks to Climate Change. K. Walter, G. Grosse, M. Edwards, L. Plug and L. Slater. Project 0732735 for National Science Foundation/International Polar Year, July 2008–June 2011.



DECODING AN *Ancient Computer*

New explorations have revealed how the Antikythera mechanism modeled lunar motion and predicted eclipses, among other sophisticated tricks

By Tony Freeth

KEY CONCEPTS

- The Antikythera mechanism is a unique mechanical calculator from second-century B.C. Greece. Its sophistication surprised archaeologists when it was discovered in 1901. But no one had anticipated its true power.
- Advanced imaging tools have finally enabled researchers to reconstruct how the device predicted lunar and solar eclipses and the motion of the moon in the sky.
- Inscriptions on the mechanism suggest that it might have been built in the Greek city of Syracuse (now in modern Sicily), perhaps in a tradition that originated with Archimedes.

—The Editors

If it had not been for two storms 2,000 years apart in the same area of the Mediterranean, the most important technological artifact from the ancient world could have been lost forever.

The first storm, in the middle of the 1st century B.C., sank a Roman merchant vessel laden with Greek treasures. The second storm, in A.D. 1900, drove a party of sponge divers to shelter off the tiny island of Antikythera, between Crete and the mainland of Greece. When the storm subsided, the divers tried their luck for sponges in the local waters and chanced on the wreck. Months later the divers returned, with backing from the Greek government. Over nine months they recovered a hoard of beautiful ancient Greek objects—rare bronzes, stunning glassware, amphorae, pottery and jewelry—in one of the first major underwater archaeological excavations in history.

One item attracted little attention at first: an undistinguished, heavily calcified lump the size of a phone book. Some months later it fell apart, revealing the remains of corroded bronze gearwheels—all sandwiched together and with teeth just one and a half millimeters long—along with plates covered in scientific scales and Greek inscriptions. The discovery was a shock: until then, the ancients were thought to have made gears only for crude mechanical tasks.

Three of the main fragments of the Antikythera mechanism, as the device has come to be known, are now on display at the Greek National Archaeological Museum in Athens. They look small and fragile, surrounded by imposing bronze statues and other artistic glories of ancient Greece. But their subtle power is even more shocking than anyone had imagined at first.

I first heard about the mechanism in 2000. I was a filmmaker, and astronomer Mike Edmunds of Cardiff University in Wales contacted me because he thought the mechanism would make a great subject for a TV documentary. I learned that over many decades researchers studying the mechanism had made considerable progress, suggesting that it calculated astronomical data, but they still had not been able to fully grasp how it worked. As a former mathematician, I became intensely interested in understanding the mechanism myself.

Edmunds and I gathered an international collaboration that eventually included historians, astronomers and two teams of imaging experts. In the past few years our group has reconstruct-

ed how nearly all the surviving parts worked and what functions they performed. The mechanism calculated the dates of lunar and solar eclipses, modeled the moon's subtle apparent motions through the sky to the best of the available knowledge, and kept track of the dates of events of social significance, such as the Olympic Games. Nothing of comparable technological sophistication is known anywhere in the world for at least a millennium afterward. Had this unique specimen not survived, historians would have thought that it could not have existed at that time.

Early Pioneers

German philologist Albert Rehm was the first person to understand, around 1905, that the Antikythera mechanism was an astronomical calculator. Half a century later, when science historian Derek J. de Solla Price, then at the Institute for Advanced Study in Princeton, N.J., described the device in a *Scientific American* article, it still had revealed few of its secrets.

The device, Price suggested, was operated by turning a crank on its side, and it displayed its output by moving pointers on dials located on its front and back. By turning the crank, the user could set the machine on a certain date as indicated on a 365-day calendar dial in the front. (The dial could be rotated to adjust for an extra day every four years, as in today's leap years.) At the same time, the crank powered all the other gears in the mechanism to yield the information corresponding to the set date.

A second front dial, concentric with the calendar, was marked out with 360 degrees and with the 12 signs representing the constellations of the zodiac [*see box on pages 56 and 57*]. These are the constellations crossed by the sun in its apparent motion with respect to the "fixed" stars—"motion" that in fact results from Earth's orbiting the sun—along the path called the ecliptic. Price surmised that the front of the mechanism probably had a pointer showing where along the ecliptic the sun would be at the desired date.

In the surviving fragments, Price identified the remains of a dozen gears that had been part of the mechanism's innards. He also estimated their tooth counts—which is all one can do given that nearly all the gears are damaged and incomplete. Later, in a landmark 1974 study, Price described 27 gears in the main fragment and provided improved tooth counts based on the first x-rays of the mechanism, by Greek radiologist Charalambos Karakalos.

ANCIENT GREEKS knew how to calculate the recurring patterns of lunar eclipses thanks to observations made for centuries by the Babylonians. The Antikythera mechanism would have done those calculations for them—or perhaps for the wealthy Romans who could afford to own it. The depiction here is based on a theoretical reconstruction by the author and his collaborators.

JEAN-FRANCOIS PODEVIN AND TONY FREETH

[THE PLACES]

The Greek and Roman worlds, circa 145 B.C.

Where Was It From?

The Antikythera mechanism was built around the middle of the 2nd century B.C., a time when Rome was expanding at the expense of the Greek-dominated Hellenistic kingdoms (*green*). Divers recovered its corroded remnants (*including fragment at left*) in A.D. 1901 from a shipwreck near the island of Antikythera. The ship sank around 65 B.C. while carrying Greek artistic treasures, perhaps from Pergamon to Rome. Rhodes had one of the major traditions of Greek astronomy, but the latest evidence points to a Corinthian origin. Syracuse, which had been a Corinthian colony in Sicily, is a possibility: the great Greek inventor Archimedes had lived there and may have left behind a technological tradition.

[THE AUTHOR]

Tony Freeth's academic background is in mathematics and mathematical logic (in which he holds a Ph.D.). His award-winning career as a filmmaker culminated in a series of documentaries about increasing crop yields in sub-Saharan Africa, featuring the late Nobel Peace Prize Laureate Norman Borlaug. Since 2000 Freeth has returned to an academic focus with research on the Antikythera mechanism. He is managing director of the film and television production company Images First, and he is now developing a film on the mechanism.

Tooth counts indicate what the mechanism calculated. For example, turning the crank to give a full turn to a primary 64-tooth gear represented the passage of a year, as shown by a pointer on the calendar dial. That primary gear was also paired to two 38-tooth secondary gears, each of which consequently turned by 64/38 times for every year. Similarly, the motion relayed from gear to gear throughout the mechanism; at each step, the ratio of the numbers of gear teeth represents a different fraction. The motion eventually transmitted to the pointers, which thus turned at rates corresponding to different astronomical cycles. Price discovered that the ratios of one of these gear trains embodied an ancient Babylonian cycle of the moon.

Price, like Rehm before him, suggested that the mechanism also contained epicyclic gearing—gears spinning on bearings that are themselves attached to other gears, like the cups on a Mad Hatter teacup ride. Epicyclic gears extend the range of formulas gears can calculate beyond multiplications of fractions to additions and subtractions. No other example of epicyclic gearing is known to have existed in Western technology for another 1,500 years.

Several other researchers studied the mechanism, most notably Michael Wright, a curator at the Science Museum in London, in collaboration with computer scientist Allan Bromley of the University of Sydney. They took the first three-dimensional x-rays of the mechanism and showed that Price's model of the mechanism had to be wrong. Bromley died in 2002, but Wright persisted and made significant advances. For example, he found evidence that the back dials, which at first look like concentric rings, are in fact spirals and discovered an epicyclic mechanism at the front that calculated the phase of the moon.

Wright also adopted one of Price's insights, namely that the dial on the upper back might be a lunar calendar, based on the 19-year, 235-lunar-month cycle called the Metonic cycle. This calendar is named after fifth-century B.C. astronomer Meton of Athens—although it had been discovered earlier by the Babylonians—and is still used today to determine the Jewish festival of Rosh Hashanah and the Christian festival of Easter. Later, we would discover that the pointer was extensible, so that a pin on its end could follow a groove around each successive turn of the spiral.

BladeRunner in Athens

As our group began its efforts, we were hampered by a frustrating lack of data. We had no access to the previous x-ray studies, and we did not even have a good set of still photographs.

KIRK CALDWELL (*map*); NATIONAL ARCHAEOLOGICAL MUSEUM, ATHENS (*fragment*); COURTESY OF COLIN FREETH (*Freeth*)

Two images in a science magazine—x-rays of a goldfish and an enhanced photograph of a Babylonian clay tablet—suggested to me new ways to get better data.

We asked Hewlett-Packard in California to perform state-of-the-art photographic imaging and X-Tek Systems in the U.K. to do three-dimensional x-ray imaging. After four years of careful diplomacy, John Seiradakis of the Aristotle University of Thessaloniki and Xenophon Moussas of the University of Athens obtained the required permissions, and we arranged for the imaging teams to bring their tools to Athens, a necessary step because the Antikythera mechanism is too fragile to travel.

Meanwhile we had a totally unexpected call from Mary Zafeiropoulou at the museum. She had been to the basement storage and found boxes of bits labeled "Antikythera." Might we be interested? Of course we were interested. We now had a total of 82 fragments, up from about 20.

The HP team, led by Tom Malzbender, assembled a mysterious-looking dome about five feet across and covered in electronic flashbulbs that provided lighting from a range of different angles. The team exploited a technique from the computer gaming industry, called polynomial texture mapping, to enhance surface details. Inscriptions Price had found difficult to read were now clearly legible, and fine details could be enhanced on the computer screen by controlling the reflectance of the surface and the angle of the lighting. The inscriptions are essentially an instruction manual written on the outer plates.

A month later local police had to clear the streets in central Athens so that a truck carrying the BladeRunner, X-Tek's eight-ton x-ray machine, could gain access to the museum. The BladeRunner performs computed tomography similar to a hospital's CT scan, but with finer detail. X-Tek's Roger Hadland and his group had specially modified it with enough x-ray power to penetrate the fragments of the Antikythera mechanism. The resulting 3-D reconstruction was wonderful: whereas Price could see only a puzzle of overlapping gears, we could now isolate layers inside the fragment and see all the fine details of the gear teeth.

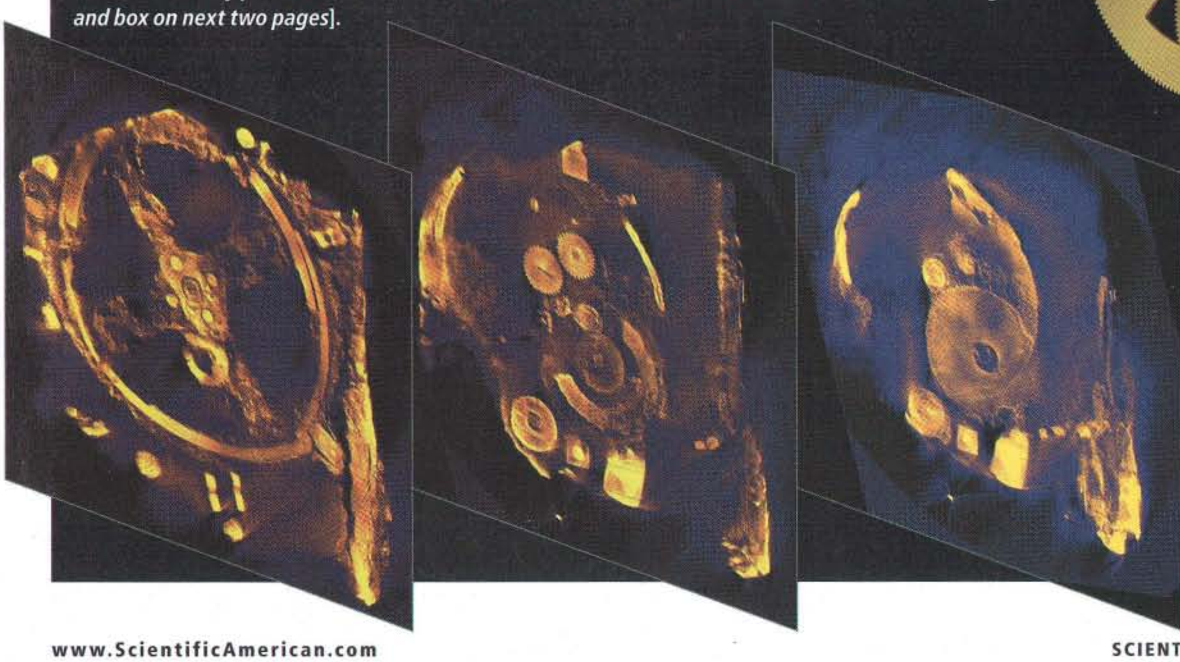
Unexpectedly, the x-rays revealed more than 2,000 new text characters that had been hidden deep inside the fragments. (We have now identified and interpreted a total of 3,000 characters out of perhaps 15,000 that existed originally.) In Athens, Moussas and Yanis Bitsakis, also at the University of Athens, and Agamemnon Tselikas of the Center for History and Palaeography be-

Historians would have thought that SOMETHING SO COMPLEX *could not have existed at the time.*

[THE RECONSTRUCTION]

Anatomy of a Relic

Computed tomography—a 3-D mapping obtained from multiple x-ray shots—enabled the author and his colleagues to get inside views of the Antikythera mechanism's remnants. For example, a CT scan can be used to virtually slice up an object (*below, slices of main fragment*). The information helped the team see how the surviving gears connected and estimate their tooth counts, which determined what calculations they performed. The team could then reconstruct most of the device [*see model at right and box on next two pages*].



gan to discover inscriptions that had been invisible to human eyes for more than 2,000 years. One translated as "... spiral subdivisions 235...," confirming that the upper back dial was a spiral describing the Metonic calendar.

Babylon System

Back at home in London, I began to examine the CT scans as well. Certain fragments were clearly all part of a spiral dial in the lower back. An estimate of the total number of divisions in the dial's four-turn spiral suggested 220 to 225.

X-rays revealed inscriptions that had been HIDDEN FROM HUMAN EYES *for more than 2,000 years.*

The prime number 223 was the obvious contender. The ancient Babylonians had discovered that if a lunar eclipse is observed—something that can happen only during a full moon—usually a similar lunar eclipse will take place 223 full moons later. Similarly, if the Babylonians saw a solar eclipse—which can take place only during a new moon—they could predict that 223 new moons later there would be a similar one (although they could not always see it: solar eclipses are visible only from specific locations, and ancient astronomers could not predict them reliably). Eclipses repeat this way because every 223 lunar months the sun, Earth and the moon return to approximately the same alignment with respect to one another, a periodicity known as the Saros cycle.

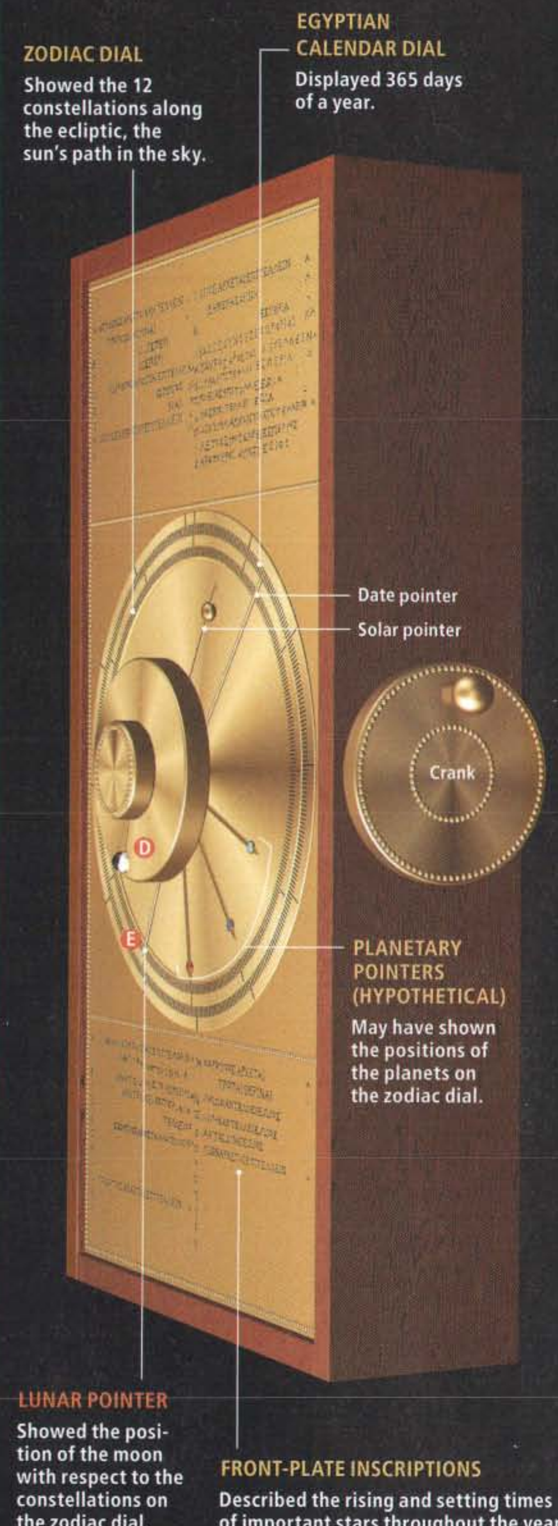
Between the scale divisions were blocks of symbols, nearly all containing Σ (*sigma*) or H (*eta*), or both. I soon realized that Σ stands for Σεληνη (*selene*), Greek for "moon," indicating a lunar eclipse; H stands for Hλιοσ (*helios*), Greek for "sun," indicating a solar eclipse. The Babylonians also knew that within the 223-month period, eclipses can take place only in particular months, arranged in a predictable pattern and separated by gaps of five or six months; the distribution of symbols around the dial exactly matched that pattern.

I now needed to follow the trail of clues into the heart of the mechanism to discover where this new insight would lead. The first step was to find a gear with 223 teeth to drive this new Saros dial. Karakalos had estimated that a large gear visible at the back of the main fragment had 222 teeth. But Wright had revised this estimate to 223, and Edmunds confirmed this. With plausible tooth counts for other gears and with the addition of a small, hypothetical gear, this 223-tooth gear could perform the required calculation.

But a huge problem still remained unsolved and proved to be the hardest part of the gearing to crack. In addition to calculating the Saros cy-

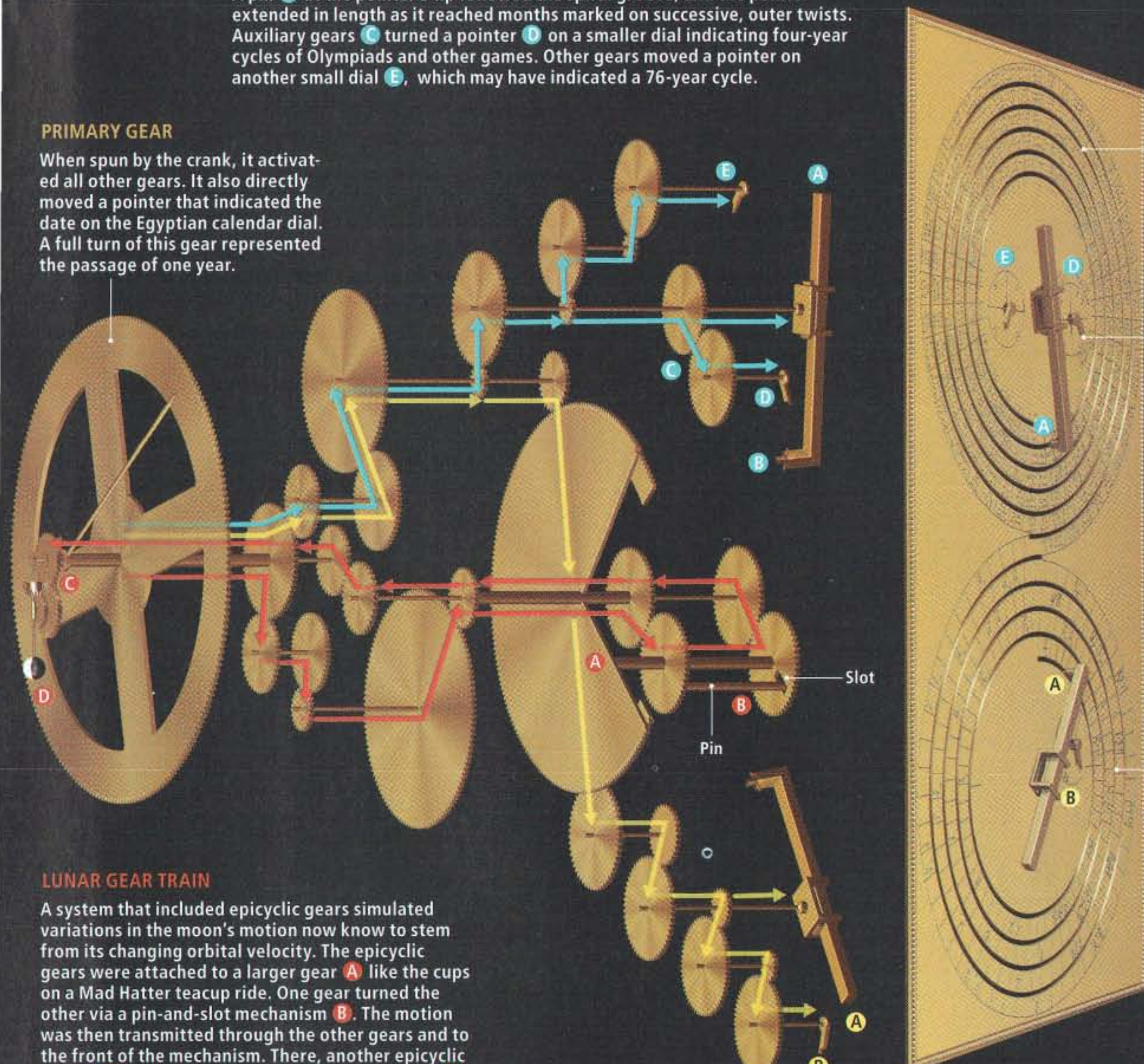
[INSIDE THE ANTIKYTHERA MECHANISM]

Astronomical Clockwork



GRIFF WASON AND TONY FREETH

This exploded view of the mechanism shows all but one of the 30 known gears, plus a few that have been hypothesized. Turning a crank on the side activated all the gears in the mechanism and moved pointers on the front and back dials: the arrows colored blue, red and yellow explain how the motion transmitted from one gear to the next. The user would choose a date on the Egyptian, 365-day calendar dial on the front or on the Metonic, 235-lunar-month calendar on the back and then read the astronomical predictions for that time—such as the position and phases of the moon—from the other dials. Alternatively, one could turn the crank to set a particular event on an astronomical dial and then see on what date it would occur. Other gears, now lost, may have calculated the positions of the sun and of some or all of the five planets known in antiquity and displayed them via pointers on the zodiac dial.



METONIC GEAR TRAIN

Calculated the month in the Metonic calendar, made of 235 lunar months, and displayed it via a pointer A on the Metonic calendar dial on the back. A pin B at the pointer's tip followed the spiral groove, and the pointer extended in length as it reached months marked on successive, outer twists. Auxiliary gears C turned a pointer D on a smaller dial indicating four-year cycles of Olympiads and other games. Other gears moved a pointer on another small dial E, which may have indicated a 76-year cycle.

PRIMARY GEAR

When spun by the crank, it activated all other gears. It also directly moved a pointer that indicated the date on the Egyptian calendar dial. A full turn of this gear represented the passage of one year.

METONIC CALENDAR DIAL

Displayed the month on a 235-lunar-month cycle arranged on a spiral.

OLYMPIAD DIAL

Indicated the years of the ancient Olympics and other games.

SAROS LUNAR ECLIPSE DIAL

Inscriptions on this spiral indicated the months in which lunar and solar eclipses can occur.

LUNAR GEAR TRAIN

A system that included epicyclic gears simulated variations in the moon's motion now know to stem from its changing orbital velocity. The epicyclic gears were attached to a larger gear A like the cups on a Mad Hatter teacup ride. One gear turned the other via a pin-and-slot mechanism B. The motion was then transmitted through the other gears and to the front of the mechanism. There, another epicyclic system C turned a half-black, half-white sphere D to show the lunar phases, and a pointer E showed the position of the moon on the zodiac dial.

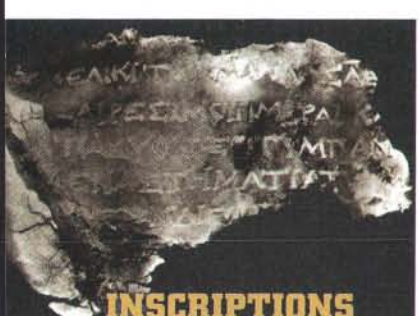
ECLIPSE GEAR TRAIN

Calculated the month in the 223-lunar-month Saros cycle of recurring eclipses. It displayed the month on the Saros dial with an extensible pointer A similar to the one on the Metonic dial. Auxiliary gears moved a pointer B on a smaller dial. That pointer made one third of a turn for each 223-month cycle to indicate that the corresponding eclipse time would be offset by eight hours.

[A USER'S MANUAL]

How to Predict an Eclipse

Operating the Antikythera mechanism may have required only a small amount of practice and astronomical knowledge. After an initial calibration by an expert, the mechanism could provide fairly accurate predictions of events several decades in the past or future. The inscriptions on the Saros dial, coming at intervals of five or six months, corresponded to months when Earth, the sun and the moon come to a near alignment (and so represented potential solar and lunar eclipses) in a 223-lunar-month cycle. Once the month of an eclipse was known, the actual day could be calculated on the front dials using the fact that solar eclipses always happen during new moons and lunar eclipses during full moons.



This fragment of the Antikythera mechanism's back, shown in x-ray imaging, contains the words "spiral subdivisions 235," which helped researchers confirm that the dial on the upper back showed the 235 months of the Metonic calendar arranged in a spiral. Previously, only the word "ΕΛΙΚΙ" (*"ELIKI," seen at top left*), Greek for "spiral," had been seen.

cle, the large 223-tooth gear also carried the epicyclic system noticed by Price: a sandwich of two small gears attached to the larger gear in teacup-ride fashion. Each epicyclic gear also connected to another small gear. Confusingly, all four small gears appeared to have the same tooth count—50—which seemed nonsensical because the output would then be the same as the input.

After months of frustration, I remembered that Wright had observed that one of the two epicyclic gears has a pin on its face that engages with a slot on the other. His key idea was that the two gears turned on slightly different axes, separated by about a millimeter. As a consequence, the angle turned by one gear alternated between being slightly wider and being slightly narrower than the angle turned by the other gear. Thus, if one gear turned at a constant rate, the other gear's rate kept varying between slightly faster and slightly slower.

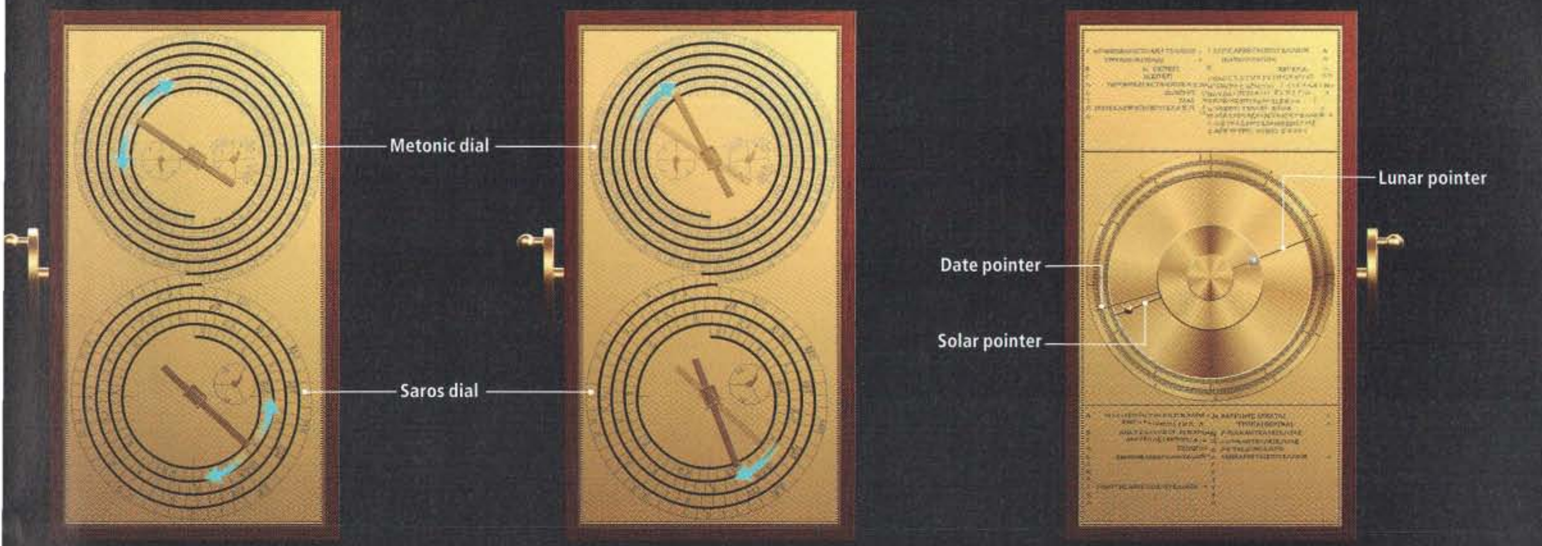
Ask for the Moon

Although Wright rejected his own observation, I realized that the varying rotation rate is precisely what is needed to calculate the moon's motion according to the most advanced astronomical theory of the second century B.C., the one often attributed to Hipparchos of Rhodes. Before Kepler (A.D. 1605), no one understood that orbits are elliptical and that the moon accelerates toward the perigee—its closest point to Earth—and slows down toward the apogee, the opposite point. But the ancients did know that the moon's motion against the zodiac appears to periodically slow down and speed up. In Hipparchos's model, the moon moved at a constant rate around a circle whose center itself moved around a circle at a constant rate—a fairly good approximation of the moon's apparent motion. These circles on circles, themselves called epicycles, dominated astronomical thinking for the next 1,800 years.

There was one further complication: the apogee and perigee are not fixed, because the ellipse of the moon's orbit rotates by a full turn about every nine years. The time it takes for the body to get back to the perigee is thus a bit longer than the time it takes it to come back to the same point in the zodiac. The difference was just 0.112579655 turns a year. With the input gear having 27 teeth, the rotation of the large gear was slightly too big; with 26 teeth, it was slightly too small. The right result seemed to be about halfway in between. So I tried the impossible idea that the input gear had 26 ½ teeth. I pressed the key on my calculator, and it gave 0.112579655—exactly the right answer. It could not be a coincidence to nine places of decimals! But gears cannot have fractional numbers of teeth.

Then I realized that $26\frac{1}{2} \times 2 = 53$. In fact, Wright had estimated a crucial gear to have 53 teeth, and I now saw that that count made everything work out. The designer had mounted the pin and slot epicyclically to subtly slow down the period of its variation while keeping the basic rotation the same, a conception of pure genius. Thanks to Edmunds, we also realized that the epicyclic gearing system, which is in the back of the mechanism, moved a shaft that turned inside another, hollow shaft through the rest of the mechanism and to the front, so that the lunar motion could be represented on the zodiac dial and on the lunar phase display. All gear counts were now explained, with the exception of one small gear that remains a mystery to this day.

Further research has caused us to make some modifications to our model. One was about a small subsidiary dial that is positioned in the back, inside the Metonic dial, and is divided into four quadrants. The first clue came when I read the word "*NEMEA*" under one of the quadrants. Alexander Jones, a New York University historian, explained that it refers to the Nemean Games, one of the major athletic events in ancient Greece. Eventually we found, engraved round the four sectors of the dial, most of "*ISTHMIA*," for games at Corinth, "*PYTHIA*," for games at Delphi, "*NAA*," for minor games at Dodona, and "*OLYMPIA*," for the most important games of the Greek world, the Olympics. All games took place every two or four years. Previously we had considered the mechanism to be



RESET DATE
Begin by turning the crank to set the current month and year on the Metonic calendar. The lower pointer will turn to the corresponding month on the Saros (*eclipse*) dial.

FIND ECLIPSE MONTH
Turn the crank to move time forward until the pointer on the Saros dial points to an eclipse inscription. The inscription will indicate month and time of the day (but not the day) of an eclipse and whether it will be solar or lunar.

CALCULATE DAY
Adjust the crank until the lunar and solar pointers are aligned (*for a solar eclipse*) or at 180 degrees (*for a lunar eclipse*). The Egyptian calendar pointer will move correspondingly and indicate the day of the eclipse.

purely an instrument of mathematical astronomy, but the Olympiad dial—as we named it—gave it an entirely unexpected social function.

Twenty-nine of the 30 surviving gears calculate cycles of the sun and the moon. But our studies of the inscriptions at the front of the mechanism have also yielded a trove of information on the risings and settings of significant stars and of the planets. Moreover, on the "primary" gearwheel at the front of the mechanism remnants of bearings stand witness to a lost epicyclic system that could well have modeled the back-and-forth motions of the planets along the ecliptic (as well as the anomalies in the sun's own motion). All these clues strongly support the inclusion of the sun and of at least some of the five planets known in ancient times—Mercury, Venus, Mars, Jupiter and Saturn.

Wright built a model of the mechanism with epicyclic systems for all five planets. But his ingenious layout does not agree with all the evidence. With its 40 extra gears, it may also be too complex to match the brilliant simplicity of the rest of the mechanism. The ultimate answer may still lie 50 meters down on the ocean floor.

Eureka?

The question of where the mechanism came from and who created it is still open. Most of the cargo in the wrecked ship came from the eastern Greek world, from places such as Pergamon, Kos and Rhodes. It was a natural guess that Hipparchos or another Rhodian astronomer built the mechanism. But text hidden between the 235 monthly scale divisions of the Metonic calendar contradicts this view. Some of the month names were used only in specific locations in the ancient Greek world and suggest a Corinthian origin. If the mechanism was from Corinth itself, it was almost certainly made before Corinth was completely devastated by the Romans in 146 B.C. Perhaps more likely is that it was made to be used in one of the Corinthian colonies in northwestern Greece or Sicily.

Sicily suggests a remarkable possibility. The island's city of Syracuse was home to Archimedes, the greatest scientist of antiquity. In the first century B.C. Roman statesman Cicero tells how in 212 Archimedes was killed at the siege of Syracuse and how the victorious Roman general, Marcellus, took away with him only one piece of plunder—an astronomical instrument made by Archimedes. Was that the Antikythera mechanism? We believe not, because it appears to have been made many decades after Archimedes died. But it could have been constructed in a tradition of instrument making that originated with the eureka man himself.

Many questions about the Antikythera mechanism remain unanswered—perhaps the greatest being why this powerful technology seems to have been so little exploited in its own era and in succeeding centuries.

In *Scientific American,* Price wrote:

It is a bit frightening to know that just before the fall of their great civilization the ancient Greeks had come so close to our age, not only in their thought, but also in their scientific technology.

Our discoveries have shown that the Antikythera mechanism was even closer to our world than Price had conceived. ■

GRIFF WASON AND TONY FREETH

MORE TO EXPLORE

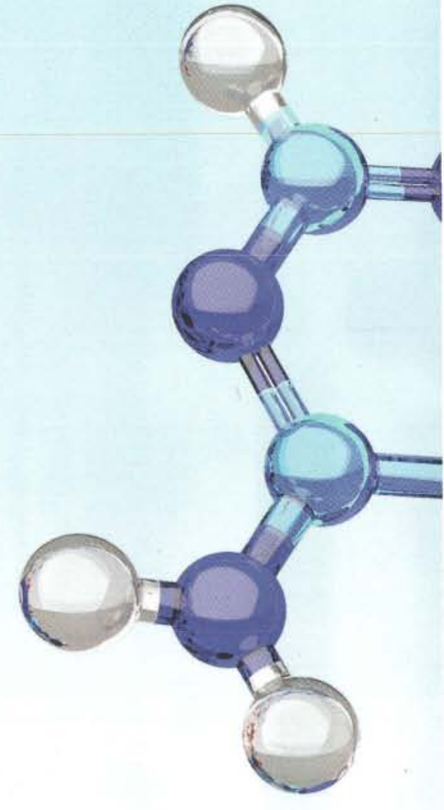
An Ancient Greek Computer. Derek J. de Solla Price in *Scientific American,* Vol. 200, No. 6, pages 60–67; June 1959.

Gears from the Greeks: The Antikythera Mechanism—A Calendar Computer from ca. 80 B.C. Derek de Solla Price in *Transactions of the American Philosophical Society,* New Series, Vol. 64, No. 7, pages 1–70; 1974.

Decoding the Ancient Greek Astronomical Calculator Known as the Antikythera Mechanism. Tony Freeth et al. in *Nature,* Vol. 444, pages 587–591; November 30, 2006.

Calendars with Olympiad Display and Eclipse Prediction on the Antikythera Mechanism. Tony Freeth, Alexander Jones, John M. Steele and Yanis Bitsakis in *Nature,* Vol. 454, pages 614–617; July 31, 2008.

The Antikythera Mechanism Research Project: **www.antikythera-mechanism.gr**



THE DOUBLE LIFE OF ATP

The molecule ATP, famous as an essential energy source inside cells, also carries critical messages between cells. That dual role is suggesting fresh ideas for fighting human diseases

BY BALJIT S. KHAKH AND GEOFFREY BURNSTOCK

KEY CONCEPTS

- ATP, best known as a universal fuel inside living cells, also serves as a molecular signal that affects cell behavior.
- A leading investigator and the discoverer of ATP's messenger role describe how ATP signals work and why they are essential to basic bodily functions and development.
- Because ATP is so ubiquitous, the molecule's influences can vary from tissue to tissue, offering new insights into a wide range of disorders and diverse ways to treat them.

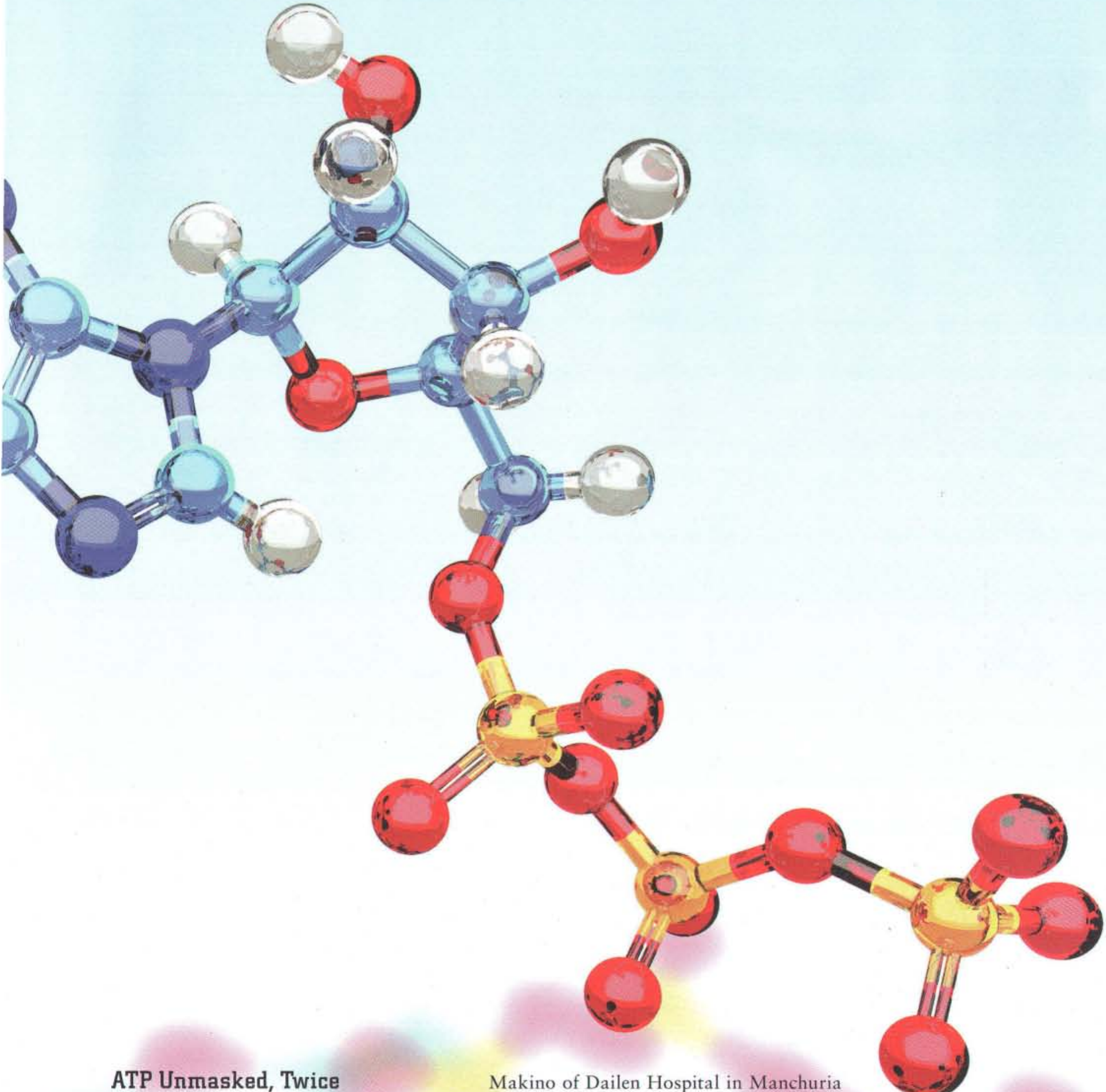
—The Editors

One of the first and most enduring facts most students learn in biology class is that all living cells use a small molecule called adenosine triphosphate (ATP) as fuel. That universal energy currency drives the biological reactions that allow cells to function and life to flourish—making ATP a crucial player in the biological world.

Less commonly known, however, is that what is perhaps the most produced and consumed molecule in the human body also has a completely separate but no less essential role outside of cells. A long series of discoveries has now demonstrated beyond doubt that ATP is a critical signaling molecule that allows cells and tissues throughout the body to communicate with one another. The universal fuel, in effect, serves as a common language as well.

When ATP's dual function was first proposed nearly 50 years ago, the idea met with considerable skepticism. But an avalanche of findings in the past 15 years has detailed how ATP acts on cells from the outside and how it serves in the development and daily operation of organs and tissues. Because ATP is so ubiquitous, its signaling actions have a uniquely broad influence on physiological functioning and offer unusually diverse opportunities to improve human health. Laboratories worldwide are now racing to turn these insights into therapies.

KEN EWARD



ATP Unmasked, Twice

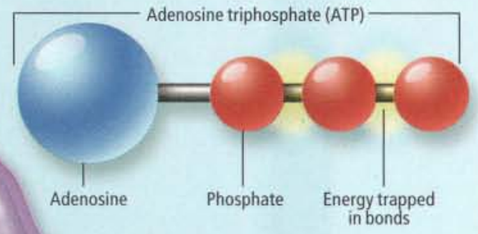
When ATP was discovered in 1929, investigators around the world were seeking the elusive source of cellular energy. In nearly simultaneous breakthroughs, Karl Lohmann, working with the 1922 Nobel Laureate Otto Meyerhof of the Kaiser Wilhelm Institute for Medical Research in Heidelberg, and Cyrus H. Fiske, working with his graduate student Yellapragada SubbaRow of Harvard Medical School, showed that intracellular activities that allow muscle cells to contract depended on a molecule made of a purine—adenosine, a combination of the base adenine with a sugar—and three phosphates. By 1935 Katashi Makino of Dailen Hospital in Manchuria had proposed a structure for the molecule, which was confirmed 10 years later, by Basil Lythgoe and Alexander R. Todd of the University of Cambridge Chemical Laboratory.

During this period no one envisioned a role for the molecule outside of the cell. That was still the case in 1962, when one of us (Burnstock) was a young neurophysiologist at the University of Melbourne in Australia, studying the nerves that control smooth muscle tissue. In the course of investigating signaling by the autonomic nervous system (which controls such basic muscle-dependent functions as intestinal and bladder contractions), he saw

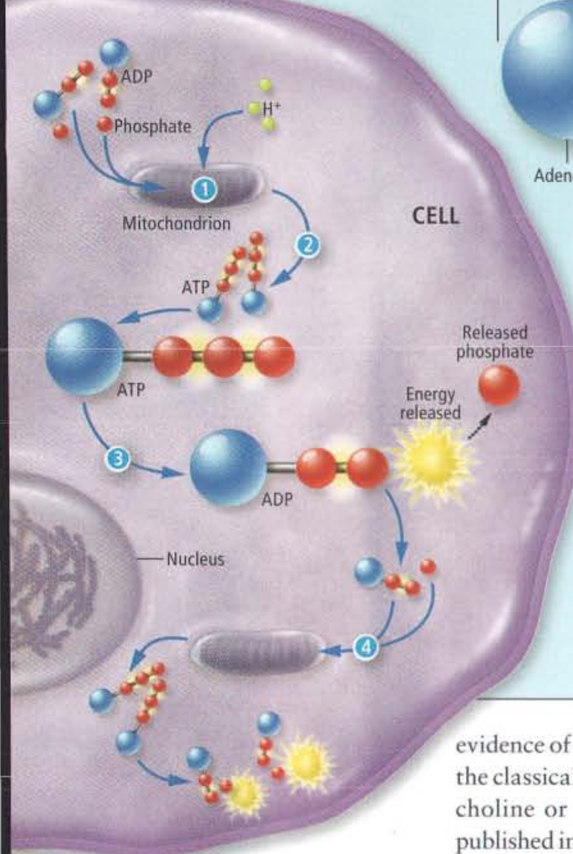
[DUAL ROLES]

ATP INSIDE CELLS . . . AND OUTSIDE

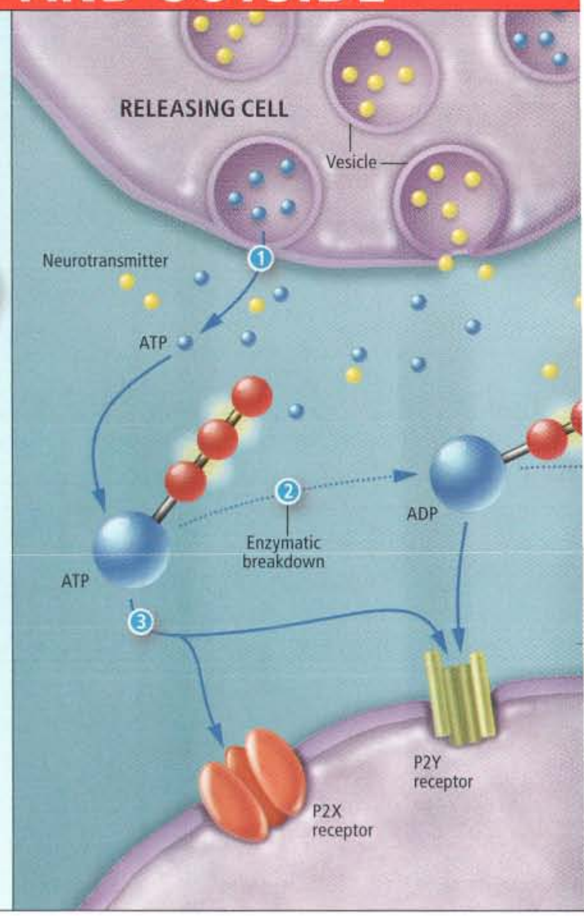
Students routinely learn that the small molecule adenosine triphosphate (ATP) is a critical cellular power source; it fuels the activities of the molecular machinery that allows all cells to function and thrive (*below*). But not all intracellular ATP is used up by cellular processes. Cells of all kinds also release ATP to send messages to nearby cells (*right*).



▲ An ATP molecule stores energy in the bonds between its three phosphates. The phosphates are anchored to adenosine, which belongs to the "purine" class of molecules.



◀ Cells manufacture ATP constantly in their mitochondria, which build it from such raw materials as protons (H^+) derived from glucose that has undergone several stages of processing. Inside mitochondria 1, protons power the addition of a phosphate to adenosine diphosphate (ADP); the resulting ATP is delivered into the cytoplasm 2. Cellular activities such as protein manufacture draw energy from ATP molecules when the terminal phosphate is released 3. ADP and free phosphates are then recycled into ATP 4.



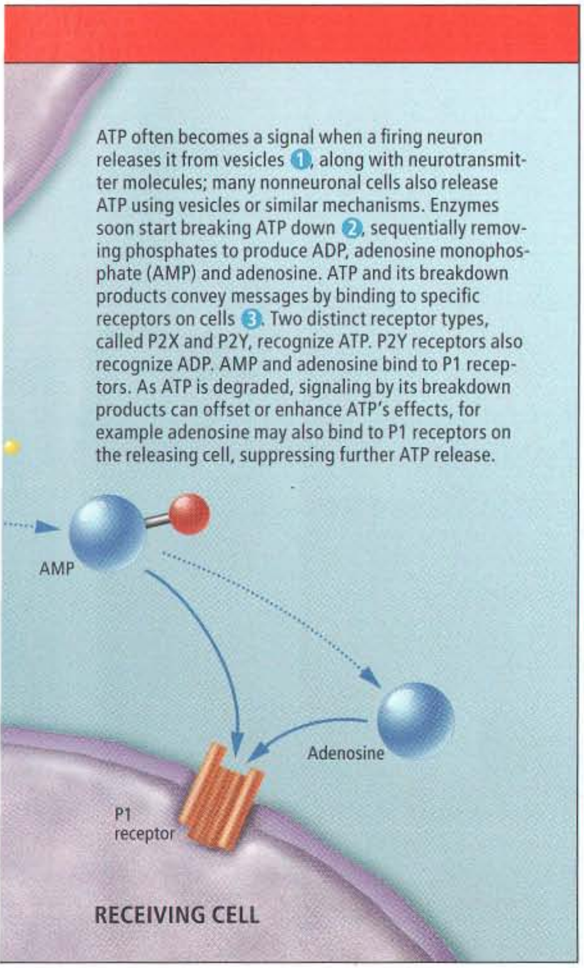
evidence of neural signaling that did not involve the classical neurotransmitter chemicals acetylcholine or noradrenaline. Intrigued by data published in 1959 by Pamela Holton of the Cambridge Physiological Laboratory suggesting that sensory nerves released ATP molecules, Burnstock set out to determine whether ATP could be responsible for signaling between motor nerves and muscle. Through a series of experiments in which he applied chemicals to block signaling by the classical neurotransmitters to smooth muscle tissue, he was able to demonstrate that any continued signaling from the nerves to the muscle had to be conveyed by ATP. Pursuing this lead for more than a decade, Burnstock felt confident enough by 1972 to propose the existence of "purinergic nerves" that release ATP as a neurotransmitter.

Nerve cells generate electrical impulses that travel the length of a single neuron, but the charge does not cross the tiny gap between the cells known as the synaptic cleft, or the gap between nerve cells and muscles. The message is forwarded from cell to cell by chemical transmitters, such as acetylcholine, glutamate, dopamine and others, released from the firing neuron into the cleft. These chemicals cross the gap and bind to receptor proteins on the receiving cell, causing that cell to undergo a series of internal changes that alter its activity; recipient neurons might fire impulses of their own, and muscle cells might contract or relax. A message can thus be transmitted down the line from neuron to neuron by an alternating series of impulses and chemical discharges.

Individual neurons were long believed to emit only a single neurotransmitter type, and cells that released acetylcholine came to be described as cholinergic; those that released dopamine, were dopaminergic, and so forth. Burnstock's concept of purinergic neurons was based not only on his own observations by that point but also on the early work of a series of outstanding students and collaborators, including Max Bennett, Graeme Campbell, David Satchell, Mollie Holman and Mike Rand of the universities of Melbourne and London.

Despite a huge amount of data showing ATP

PRECISION GRAPHICS



ATP often becomes a signal when a firing neuron releases it from vesicles 1, along with neurotransmitter molecules; many nonneuronal cells also release ATP using vesicles or similar mechanisms. Enzymes soon start breaking ATP down 2, sequentially removing phosphates to produce ADP, adenosine monophosphate (AMP) and adenosine. ATP and its breakdown products convey messages by binding to specific receptors on cells 3. Two distinct receptor types, called P2X and P2Y, recognize ATP. P2Y receptors also recognize ADP. AMP and adenosine bind to P1 receptors. As ATP is degraded, signaling by its breakdown products can offset or enhance ATP's effects, for example adenosine may also bind to P1 receptors on the releasing cell, suppressing further ATP release.

release from neurons into muscle, gut and bladder tissue, many neurophysiologists nonetheless remained skeptical about the existence of nerves releasing ATP as a messenger, largely because they thought it unlikely that such a ubiquitous substance could perform such a specific role. Moreover, for a signaling molecule to be able to function, it must find a suitable receptor on its target cell. The first receptor for a neurotransmitter had been isolated only in 1970; therefore, the hunt was on for the receptors for ATP.

Well before they were found, however, many researchers continued to use pharmacological methods to examine how ATP released by neurons delivered messages into muscle and other cells of the body. Based on this work, Burnstock suggested in 1978 that separate families of receptors existed for ATP (which he designated P2 receptors) and for its final breakdown product, adenosine (which he called P1 receptors). Further studies showed that ATP activation of P2 receptors could produce different cellular effects. That led Burnstock and his collaborator Charles Kennedy to anticipate the existence of P2 receptor subtypes, which they named P2X and P2Y.

Still, the idea of nerves that released ATP as a neurotransmitter remained controversial and was dismissed by many for years to come. In the 1990s, though, molecular tools became available that allowed many research groups to isolate ATP receptors and to further explore their many fascinating effects on cells of the nervous system and beyond.

Interplay and Dynamics

The early 1990s saw the initiation of the Human Genome Project and the beginning of an era of prolific discovery of the genes that encode important proteins in the human body. Among these genes were several for ATP receptors, which allowed scientists to locate the receptors themselves on many different cell types. Studies of ATP signaling entered a new and exciting era. Attempts to characterize the molecular structure of purine receptors proved the existence of a large family of receptors and identified a number of channels and enzymes on the surface of cells that participate in ATP signaling.

As predicted, two broad classes of receptor were identified, but the work also revealed many more receptor subtypes than expected within those classes. This diversity implied that particular receptor subtypes could be targeted with highly selective drugs to modulate ATP signaling only in specific tissues or cell types—a prospect that is bearing fruit today [*see table on page 67*].

After the initial isolation of ATP receptors, various investigators showed that the two main classes operate in significantly different ways. P2X receptors belong to a "superfamily" of transmitter-gated ion channels. One of us (Khakh), along with other investigators, showed that when bound by ATP, P2X receptors literally open to form a channel that allows sodium and large amounts of calcium ions to rush into cells. P2Y receptors, in contrast, do not open in the same way, but ATP binding to their extracellular surface sets off a cascade of molecular interactions inside cells that results in intracellular calcium stores being released. In both cases, the calcium can then set off further molecular events that alter cell behavior.

Although ATP stays in the synaptic cleft only briefly, the cellular effects of receptor activation can occur quickly in some instances—within milliseconds—but slowly in others—sometimes over the course of years. For example, an inrush

ATP SIGNALING: A BRIEF HISTORY

1929 ATP discovered to be the energy source in muscle tissue.

1929 Albert Szent-Györgyi finds purines (ATP's chemical family) have potent effects on the heart. ▼

Albert Szent-Györgyi

1945 ATP structure confirmed.

1959 Pamela Holton shows ATP release from sensory nerves.

1962 Geoffrey Burnstock demonstrates message transmission from neurons to muscle by a new neurotransmitter. ▼

Mollie Holman and Burnstock, 1962

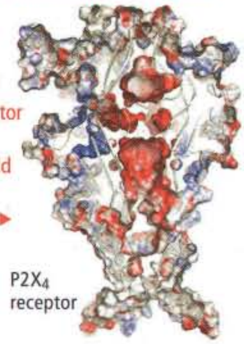
1972 Burnstock proposes the existence of nerves that signal using ATP.

1976 Burnstock proposes that ATP acts as a co-transmitter with other neurotransmitters.

1993 and 1994 P2X and P2Y receptors for ATP isolated from cells.

1998 Clopidogrel, a drug that acts on platelet P2Y receptors, introduced to prevent clot formation in blood vessels.

2009 Crystal structure of a P2X receptor revealed, which should aid drug discovery. ►



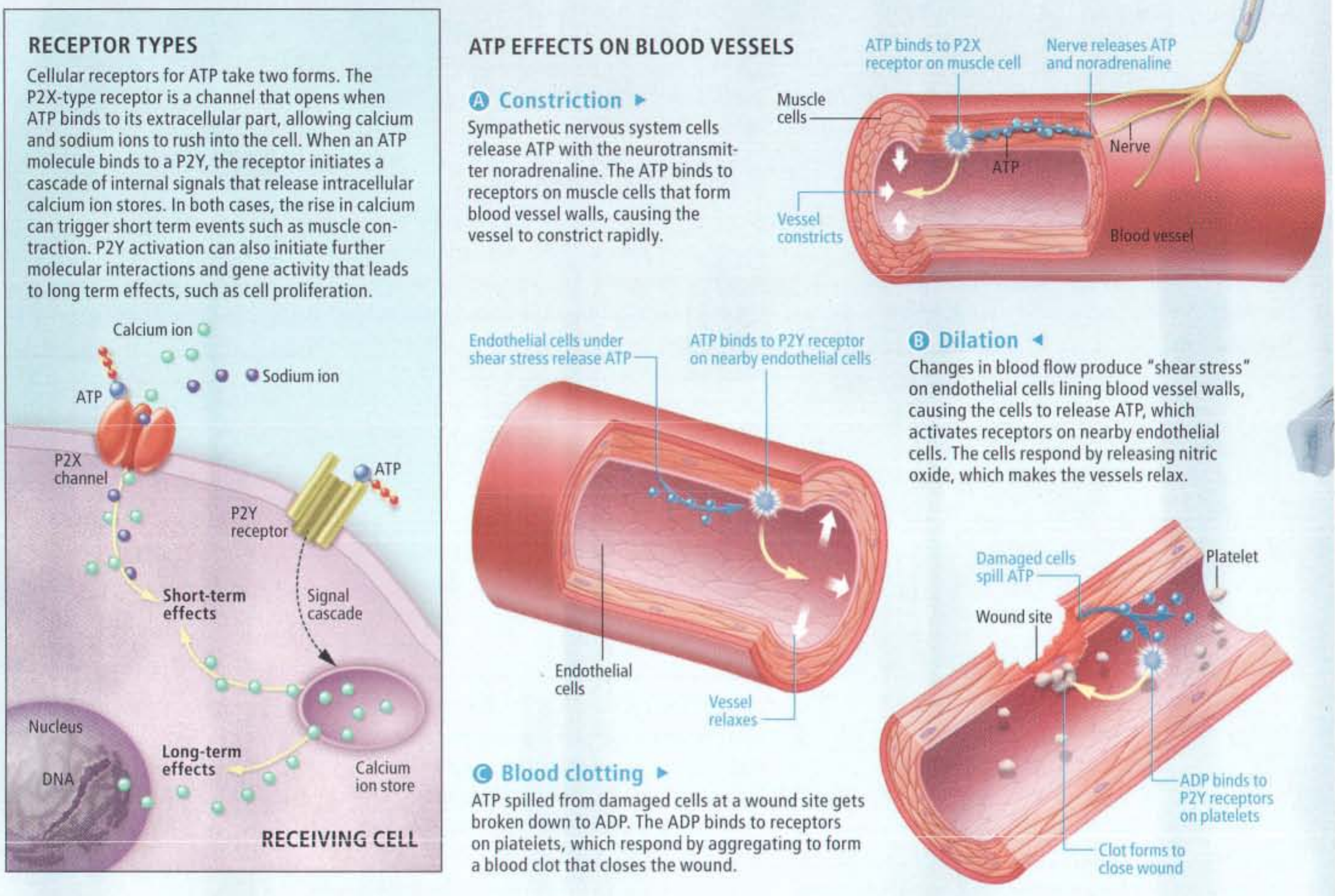
$P2X_4$ receptor

JOHN PHILLIPS *Getty Images* (*Szent-Györgyi*); COURTESY OF GEOFFREY BURNSTOCK (*Holman and Burnstock*); FROM "CRYSTAL STRUCTURE OF THE ATP-GATED P2X4 ION CHANNEL IN THE CLOSED STATE," BY TOSHIMITSU KAWATE, JENNIFER CARLISLE MICHEL, WILLIAM T. BIRDSONG AND ERIC GOUAUX, IN *NATURE*, VOL. 460; JULY 30, 2009. REPRINTED WITH PERMISSION FROM MACMILLAN PUBLISHERS LTD. (*ATP crystals*)

[ATP IN ACTION]

ONE SIGNAL, MANY MESSAGES

ATP-signaling activity was first detected between nerve cells and muscle tissue but is now known to operate within a wide variety of cell types in the body. Select examples from the cardiovascular system illustrate how diverse ATP's effects can be in their nature and duration.



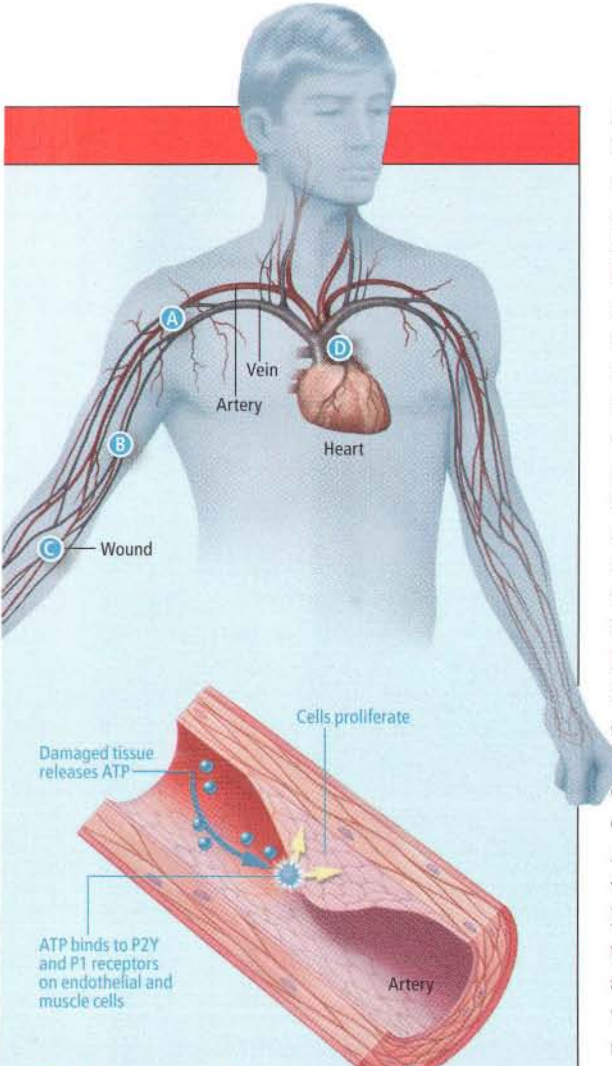
of calcium ions through P2X channels may cause the cell to release other transmitters, as Khakh has shown in brain tissue, or calcium released by P2Y activation may alter gene activity involved in cell proliferation that causes changes in the tissue with lifelong consequences. Even though the presence of ATP molecules in the extracellular space is fleeting, therefore, their biological effects can be quite pervasive.

The mechanisms of ATP signaling become even more fascinating when its interactions with other signaling systems outside of cells are taken into account. A large family of enzymes known as ectoATPases sit on the surface of most cells, where they quickly strip ATP of its phosphates one by one—sequentially turning an ATP molecule into adenosine diphosphate (ADP), adenosine monophosphate (AMP) and finally adenosine alone. Each of ATP's breakdown products may have an effect of its own on a cell—such as when adenosine binds to P1 receptors.

Fusao Kato of the Jikei University School of Medicine in Tokyo has shown, for instance, that ATP and adenosine act in concert in the brain stem network responsible for basic body functions such as breathing, heart rhythm and gastrointestinal action. Other situations exist, however, where ATP and adenosine oppose each other, such as during neuron-to-neuron transmission, where adenosine can inhibit a neuron from releasing ATP into the synaptic cleft. The interconnected effects of ATP, its component parts and the extracellular ectoATPases can thus be seen as forming a self-regulating signaling loop in many circumstances.

It is not only ATP breakdown products that influence the molecule's effects on cells. In the nervous system, ATP also acts in concert with

PRECISION GRAPHICS



D Cell proliferation ▲

After surgery to clear a partially blocked artery, ATP released from damaged tissue binds to receptors on endothelial and muscle cells, inducing the cells to multiply. The result can be a lasting renarrowing of the artery called restenosis.

other neurotransmitters as a co-transmitter. Discovery of this phenomenon in 1976 by Burnstock helped to revise the long-standing view that any given neuron can synthesize, store and release just one kind of neurotransmitter. Today a substantial body of evidence shows that ATP is typically released along with classical neurotransmitters, such as noradrenaline or acetylcholine. Although co-transmission was first proposed and proved for ATP, the phenomenon of neurons that co-release transmitter molecules has now also been demonstrated for a variety of other transmitters, including GABA with glycine, dopamine with serotonin, and acetylcholine with glutamate. Co-transmission is thus another example of how studies of ATP signaling have revealed more general physiological principles as well as shaped and guided research in other fields.

ATP in Health and Disease

In light of ATP's established role in signaling among cells of the nervous system, it may come as no surprise that ATP plays an important part in the functioning of the five senses. In the eye, for example, ATP receptors on nerve cells in the retina influence the cells' responses to information received from rods and cones, the eyes' light detectors. The retinal nerves, in turn, dispatch ATP and acetylcholine as co-transmitters to convey their information to sensory-processing centers in the brain. In addition to this everyday function for ATP, several research groups have shown that ATP signaling at a key point during an embryo's eye development can have effects that last a lifetime. Indeed, Nicholas Dale of the University of Warwick in England and his colleagues have shown that release of ATP at a critical time in the early embryo is the signal for the development of eyes.

Release of ATP during development is also essential for the proper formation of the cochlea, the organ responsible for hearing, and ATP signaling continues to be crucial to the workings of the inner ear in adults. Some 50,000 hair cells—the sound-transducing neurons of the inner ear—line the human cochlea, and about half of those display receptors for ATP, which has been shown to ease neural firing in some circumstances. In addition, taste buds, the sensory nerve endings in the tongue, possess P2X receptors that mediate taste. In a particularly well-designed study, Sue C. Kinnamon and her colleagues at Colorado State University have demonstrated that ATP is vital as a transmitter from taste bud cells to gustatory nerves and that mice lacking both $P2X_2$ and $P2X_3$ receptor subtypes are incapable of tasting.

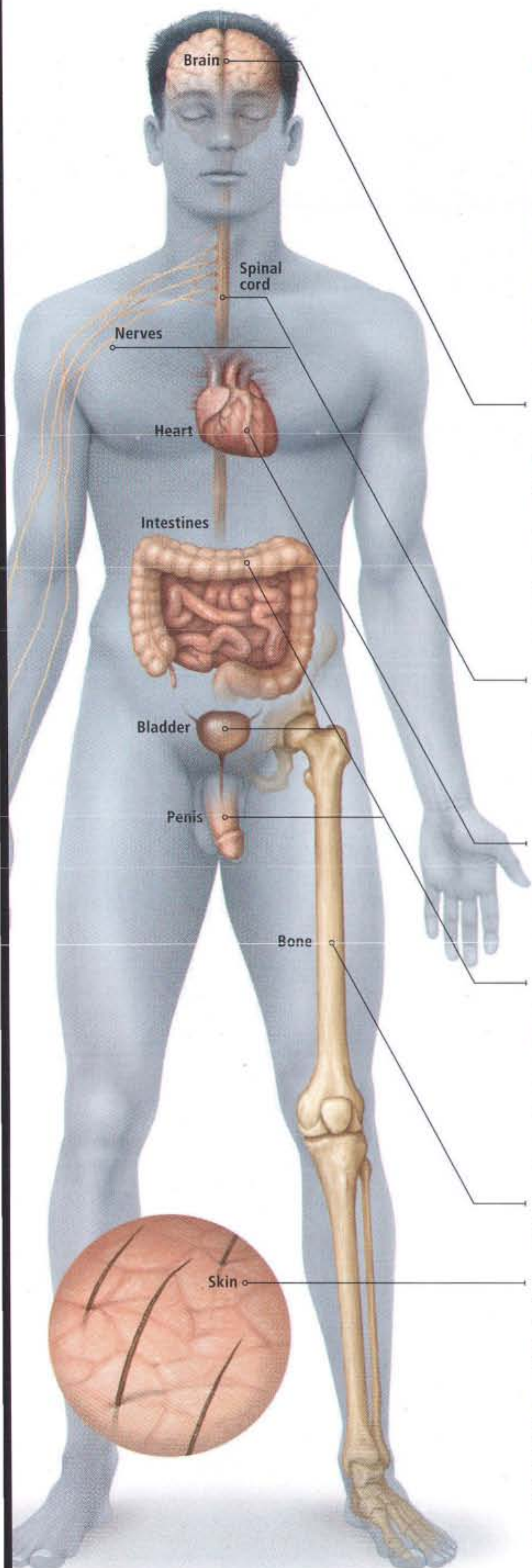
Interestingly, the $P2X_2$ and $P2X_3$ receptors present on taste buds are the same ones involved in certain types of pain signaling. For decades scientists have known that ATP introduced into the skin causes pain. Stephen B. McMahon and his colleagues at Guy's, King's and St. Thomas' School of Biomedical Sciences in London, recently showed that the pain is triggered by the activation of $P2X_3$ ATP receptors on the sensory nerve endings in the skin that mediate responses to both touch and pain. Another form of pain, one associated with damage to nerves, is called neuropathic pain and involves ATP by a different route. Elegant studies from Kazuhide Inoue of Kyushu University in Japan and Michael Salter of the University of Toronto show that a key step in the development of this type of pain in-

[THE AUTHORS]

Baljit S. Khakh is an assistant professor of physiology and neurobiology at the David Geffen School of Medicine at the University of California, Los Angeles. He has developed novel tools, such as designer ATP receptors that can be monitored by light, to probe how cells sense and respond to ATP. **Geoffrey Burnstock**, the first to show that ATP acts as a signaling molecule, was chair of the department of anatomy and developmental biology at University College London for 22 years and is now president of the Autonomic Neuroscience Center at the Royal Free and University College Medical School in London. He has won numerous awards and honors. He and Khakh met in 1994 at a coffee shop in Vienna, where they discussed ATP over apple strudel.

EARLY ORIGIN

The discovery of ATP receptors in plants and primitive life-forms, such as amoebas and worms, suggests that the molecule took on a signaling role very early in the evolution of life. In the slime mold *Dictyostelium discoideum* (*below*), ATP-activated receptors that resemble human P2X channels control the flow of water into and out of cells.



ANATOMY OF ATP

As a neurotransmitter, ATP is directly involved in brain function, sensory perception, and nervous system control of muscles and organs. When released by nonneuronal cells, it often triggers protective responses, such as bone building and cell proliferation. Below are some areas where efforts are under way to understand and exploit ATP's many roles.

BRAIN: ATP modulates communication among neurons and between neurons and support cells called glia. Signaling by ATP and its breakdown product adenosine is involved in sleep, memory, learning, movement and other brain activities, and excessive signaling may be involved in epilepsy and some psychological disorders. ATP also stimulates tissue development and repair following injury but may promote cell death in neurodegenerative diseases.

SENSORY ORGANS AND PAIN PATHWAYS: ATP regulates, and in some cases conveys, information flowing from sensors in the eyes, ears, nose and tongue to the brain. Pain-sensing nerves also use the molecule to transmit signals to the spinal cord.

HEART: ATP co-released with noradrenaline from autonomic nerves stimulates heart muscle contractions. Dysfunction of this signaling pathway causes arrhythmias and blood pressure changes.

OTHER ORGANS: Normal intestinal contractions and enzyme secretions during digestion are heavily influenced by ATP signaling from nerves in the gut. Bladder contraction and control is also regulated by ATP, and penis erection and relaxation require ATP signals from nerves to smooth muscle and to endothelial cells, which in turn release muscle-relaxing nitric oxide.

BONE: Activation of ATP receptors stimulates bone-building cells and represses bone-destroying cells.

SKIN: ATP receptors mediate skin cell turnover in normal regeneration, wound healing, and possibly in cell-proliferation disorders such as psoriasis and scleroderma.

IMMUNE SYSTEM: ATP released from injured tissue provokes immune cells to cause inflammation, a healing response that can also cause pain; excessive and prolonged inflammation can damage tissue, as in rheumatoid arthritis. ATP signaling also helps immune cells to kill bacteria-infected cells.

volves activation of ATP receptors on spinal cord immune cells called microglia. The microglia, in turn, release molecules that irritate nerve fibers, leading to chronic pain [see "New Culprits in Chronic Pain," by R. Douglas Fields; SCIENTIFIC AMERICAN, November 2009].

Because of such insights into ATP's signaling role, several pharmaceutical companies are now pursuing P2X receptors as new drug targets for neuropathic pain or pain caused by inflammation. And pain is but one aspect of human health that may soon benefit from therapies aimed at ATP or its receptors.

People with heart and blood vessel disorders are among those who stand to benefit from future drugs that act on ATP receptors. The reason becomes clear when one looks at the events that follow an injury. Cells that are distressed or physically damaged can release or spill ATP into the extracellular space. In those situations, ATP signaling often results in protective and healing responses, including by blood platelets, the cells responsible for forming a clot to stop bleeding from a new wound. Platelets display the $P2Y_{12}$ receptor subtype, and its activation by extracellular ATP causes them to undergo changes that lead to clot formation. Of course, this same process contributes to the formation of the clots in blood vessels that can cause heart attacks and stroke. An existing "blockbuster" drug, clopidogrel, works by blocking the $P2Y_{12}$ receptor on platelets and thereby preventing ATP from promoting clots. A handful of drugs that function in related ways are also in advanced clinical trials for coronary disorders.

A similarly promising therapeutic area is the digestive system. James J. Galligan of Michigan State University and others have demonstrated that ATP sent from the intestinal nervous system to the intestinal wall acts on P2X and P2Y receptors to control the rhythmic contractions that move food through the tract. Meanwhile ATP that binds to P2Y receptors on cells lining the inner surface of the gut wall triggers secretion of digestive enzymes. Agents that act on those receptors to modulate these functions are therefore being hotly pursued by pharmaceutical companies as potential treatments for irritable bowel syndrome and its more severe form, Crohn's disease.

The involvement of ATP in healthy functioning of other organs and tissues makes it a possible drug target in a long list of disorders, including diseases of the kidney, bone, bladder, skin, and even neurological and psychiatric ill-

PRECISION GRAPHICS

nesses. What is more, ATP may be one of the body's natural cancer-fighting tools. Eliezer Rapaport, when at the Boston University School of Medicine, first described a tumor-killing effect of ATP in 1983. He, too, was met with skepticism, but research since then by a number of laboratories working independently has shown that ATP can inhibit the growth of tumors, including prostate, breast, colorectal, ovarian and esophageal cancers, as well as melanoma cells. ATP signaling acts in part to promote suicide of the tumor cells and in part to promote cell differentiation, which slows tumor cell proliferation.

Much work remains to be done to translate new insights into ATP signaling gathered so far into novel medicines ready for use in the clinic. But many laboratories and drug companies are actively looking for drugs that can selectively activate or silence specific ATP receptor subtypes, inhibit or enhance the release of ATP, or inhibit the breakdown of ATP after it has been released from cells.

The Ultimate Messenger

ATP's ubiquity as a signaling molecule does pose at least one major challenge: developing drugs targeted only to a single organ or tissue without causing side effects in other body systems. This concern is not unique to ATP, however, and the great variety of subunit configurations found on different cell types will make targeting specific tissues more feasible. Khakh has been experimenting with creating "designer" ATP receptors that can be incorporated into cultured cells or even living laboratory mice and used to test the effects of subtly changing the function of a P2X receptor protein. This is just one approach that allows researchers to manipulate ATP signaling in a controlled manner and study the results in living organisms.

One of the most important breakthroughs in the past 20 years has been the recent determination of the crystal structure of a zebra fish P2X channel by Eric Gouaux and his colleagues at Oregon Health and Science University. This landmark achievement shows atomic-scale details of how an ATP receptor works and paves the way for an understanding of ATP signaling from the level of molecules to that of whole physiological systems. It will also significantly accelerate the process of drug discovery.

Recent evidence of ATP receptors in plants and primitive organisms, such as green algae, amoebas and parasitic schistosomes, offers the possibility that targeting ATP signaling may also be useful in agriculture and in the treatment of infectious diseases. The presence of ATP signaling in such diverse life-forms suggests, too, that ATP's function as a signaling molecule appeared early in the evolution of life—perhaps more or less simultaneously with its adoption as an energy source. Many reports of potent effects caused by ATP and its derivatives in most invertebrate and lower vertebrate animals also suggest that ATP's influence could be widespread indeed.

It is gratifying for us to see how the role of ATP as a signaling molecule has gone from an idea that was widely deemed dubious 50 years ago to a large and vibrant field of inquiry today of interest to the entire biology community and of great potential import to medicine. We look forward to seeing how further breakthroughs in understanding the fascinating double life of ATP are exploited to improve the quality of human life. ■

[DRUGS]

TARGETING ATP RECEPTORS

Identification of the specific receptor subtypes responsible for ATP's signaling effects in various tissues has allowed pharmaceutical companies to begin developing therapies for a range of disorders. Two of the drugs listed below are already marketed; the rest are still under study.

DISORDER	DRUG	MECHANISM	TESTING STAGE
Cystic fibrosis	Denufosol	Activates $P2Y_2$ receptors	Late-stage human efficacy tests under way
Dry eye	Diquafosol	Activates $P2Y_2$ receptors	Late-stage human efficacy tests under way
Inflammation	EVT 401	Inhibits $P2X_7$ receptors	Human safety tests completed
Pain	GSK1482160	Inhibits $P2X_7$ receptors	Human safety tests under way
	Unnamed compounds (from Evotec AG)	Inhibit $P2X_3$ and $P2X_{2/3}$ receptors	Cell and animal testing
Rheumatoid arthritis	CE-224,535	Inhibits $P2X_7$ receptors	Late-stage human efficacy tests completed
	AZD9056	Inhibits $P2X_7$ receptors	Human safety tests completed
Thrombosis (aberrant blood clotting)	Clopidogrel	Inhibits $P2Y_{12}$ receptors	Approved
	Prasugrel	Inhibits $P2Y_{12}$ receptors	Approved
	PRT060128	Inhibits $P2Y_{12}$ receptors	Human safety and efficacy tests under way
	Ticagrelor	Inhibits $P2Y_{12}$ receptors	Late-stage human efficacy tests under way

➡ MORE TO EXPLORE

Molecular Physiology of P2X Receptors and ATP Signalling at Synapses. Baljit S. Khakh in *Nature Reviews Neuroscience*, Vol. 2, pages 165–174; March 2001.

Pathophysiology and Therapeutic Potential of Purinergic Signaling. Geoffrey Burnstock in *Pharmacological Reviews*, Vol. 58, No. 1, pages 58–86; March 2006.

P2X Receptors as Cell-Surface ATP Sensors in Health and Disease. Baljit S. Khakh and R. Alan North in *Nature*, Vol. 442, pages 527–532; August 3, 2006.

Physiology and Pathophysiology of Purinergic Neurotransmission. Geoffrey Burnstock in *Physiological Reviews*, Vol. 87, No. 2, pages 659–797; April 2007.

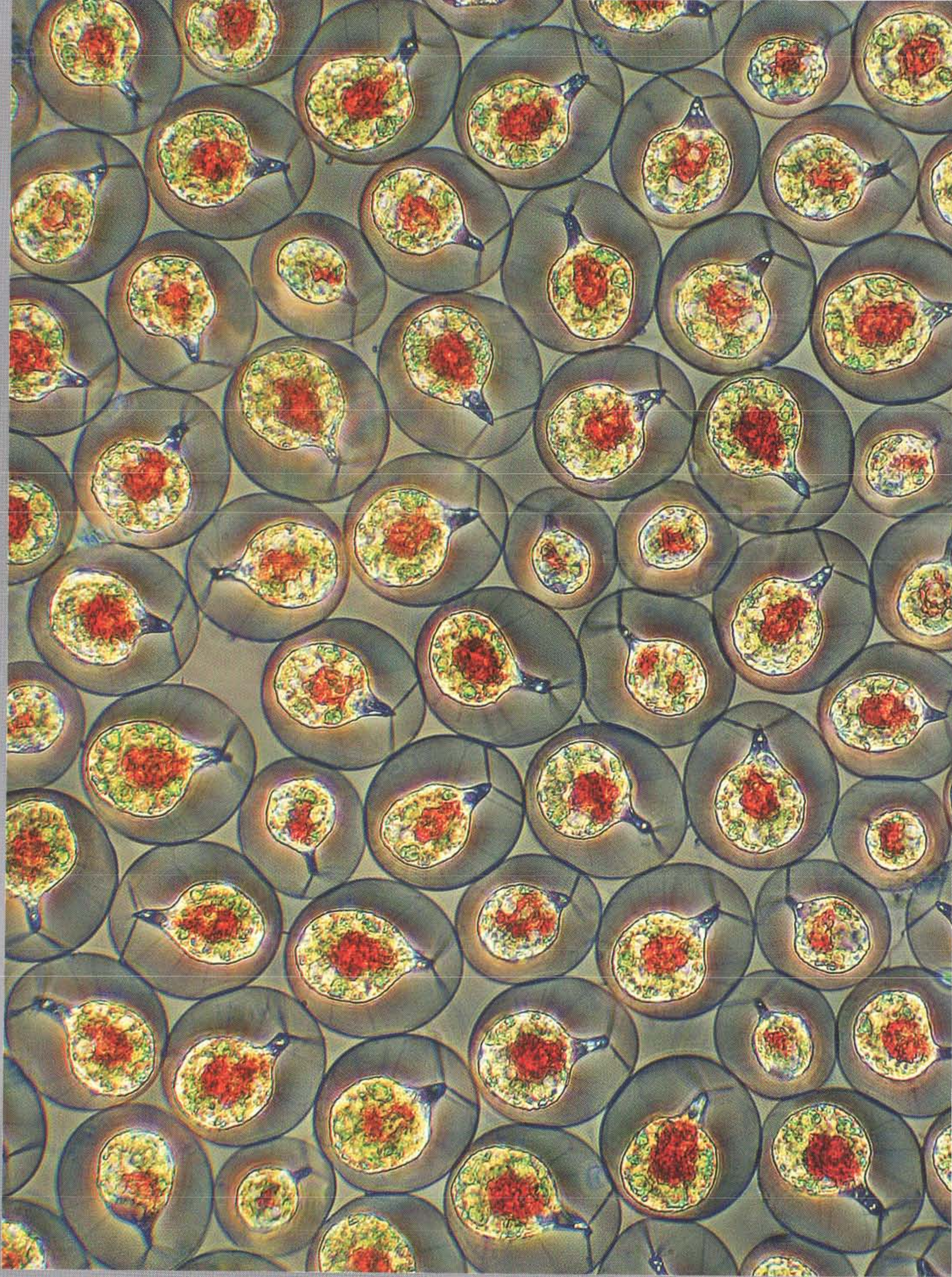
Illuminating the {Lilliputian}

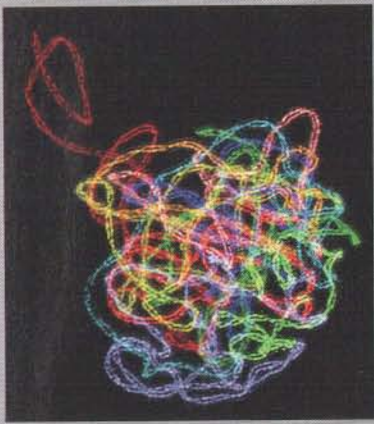
A gallery of images captured by light microscopy reveals the high art of the natural world • By Gary Stix

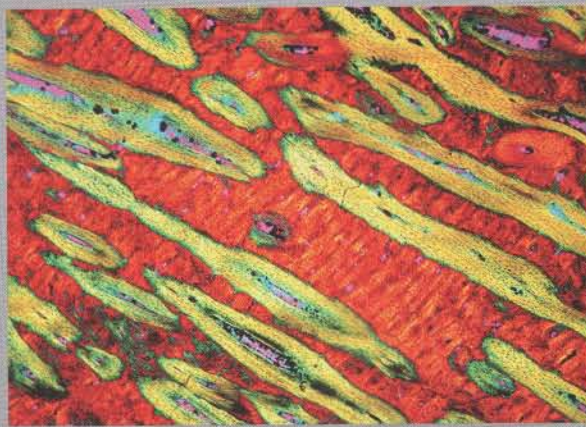
We are approaching the millennial anniversary of the first meaningful written description of how lenses and light could be used to magnify objects. It was in 1011 that Arab scientist Ibn al-Haytham (Alhazen) began writing the *Book of Optics*, which described the properties of a magnifying glass, principles that later led to the invention of the microscope. The entrants in the 2009 Olympus BioScapes Digital Imaging Competition provide fitting tribute to nearly 1,000 years of making the invisible visible.

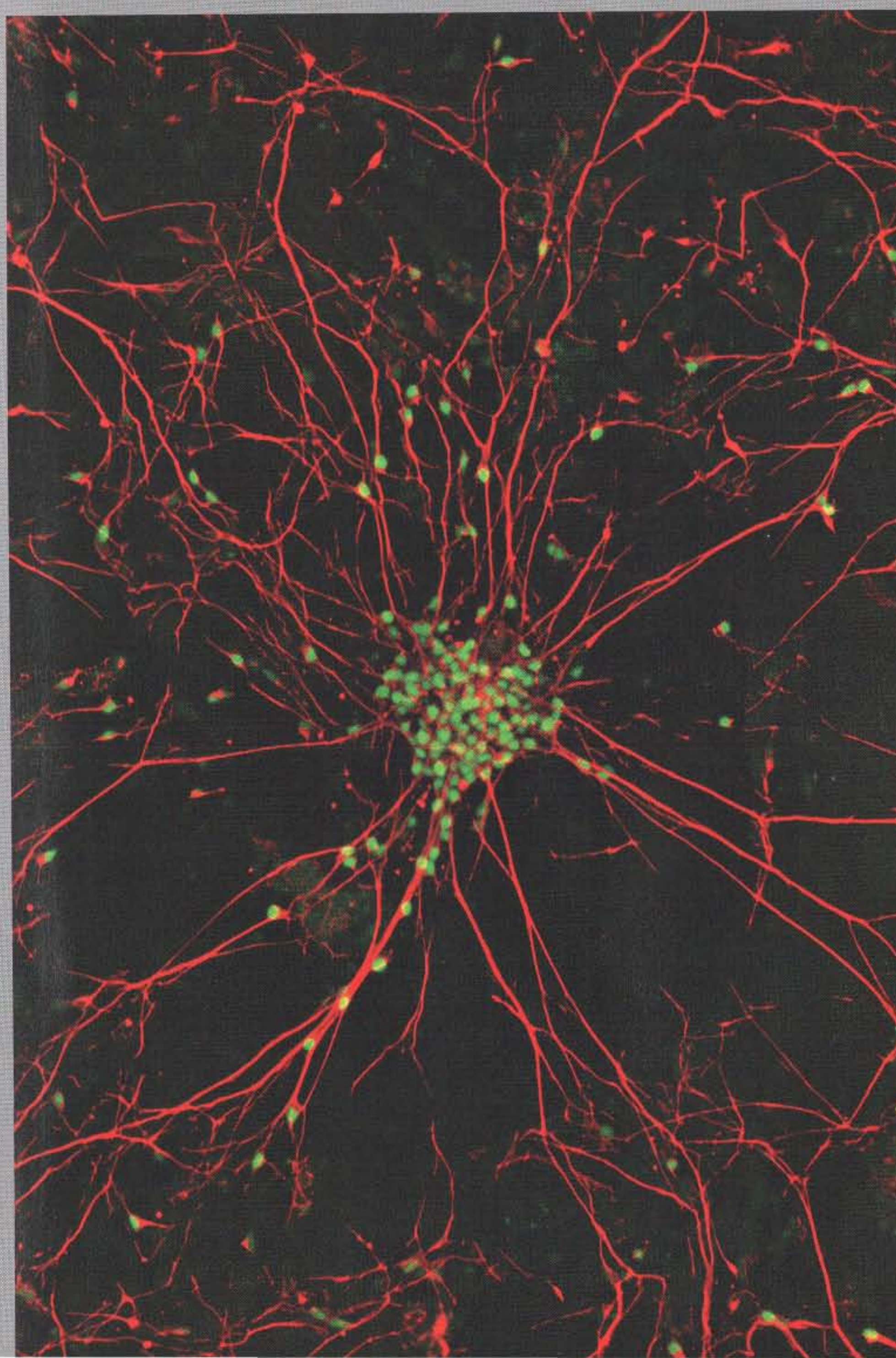
Optical microscopy, energized by generation after generation of technological advance, continues to furnish dazzling proof that beyond the resolution of the human eye resides a sweepingly large world of small things, both around and within us. The artistic beauty of the microcosm can be witnessed in these photographs of the beadlike band of toxin-carrying compartments on the tentacle of the Portuguese man-of-war, the gemlike quality of row on row of single-celled algae and the red-and-yellow patterning of a *Triceratops* bone, reminiscent of a loud necktie. A selection of winning and honorable mention images that particularly appealed to us at *Scientific American* follows.

Deadly tentacle of a Portuguese man-of-war stands out as a delicate pink ribbon containing toxin-filled beads (each about 300 microns in diameter) that can be released in the presence of prey or by inadvertent contact with an unwitting human victim. Alvaro E. Migotto of the University of São Paulo captured this photomicrograph soon after a floating colony of *Physalia physalis* was plucked from a canal near the university's center for marine biology. The muscle bands, responsible for the tentacle's flexibility, appear as whitish, winding lines in the background.







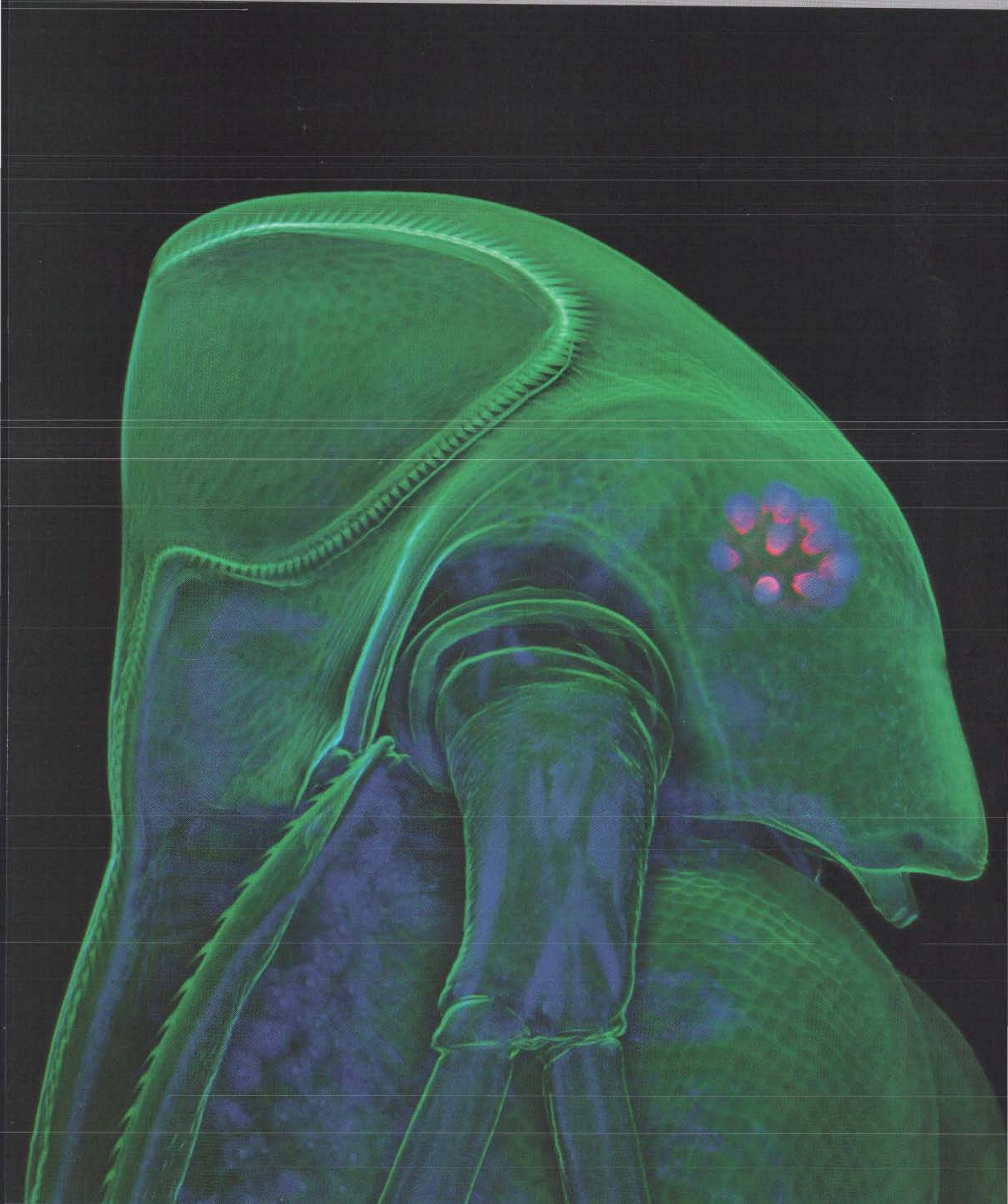


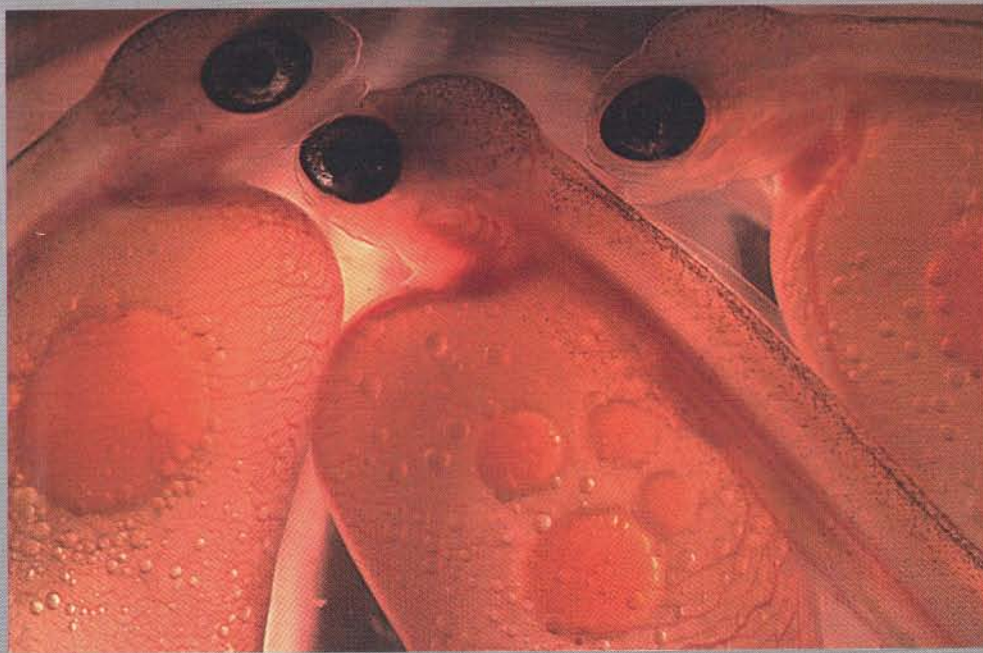
FACING PAGE
Gem-quality algae, each a single cell about 40 microns in diameter, exhibit the red coloration of the carotenoid pigment astaxanthin in their interiors. Astaxanthin made by such algal cells is exploited to make salmon pinker. Charles Krebs, a professional photographer from Issaquah, Wash., employed phase-contrast illumination for capturing this picture of a sample from an outdoor birdbath.

THIS PAGE, TOP LEFT
Core of corn emerges in this close-up of the nucleus of a plant cell undergoing meiosis, a form of cell division. Chung-Ju Rachel Wang of the University of California, Berkeley, deployed a technique called 3-D structured illumination microscopy to produce high-resolution images of parts of synaptonemal complexes: specifically, two protein strands aligned in parallel, no more than 200 nanometers apart, that provide structural support to chromosomes (*not shown*) during meiosis. The powerful new technique revealed the twisted helical structures of 10 such complexes, each digitally colored to distinguish one from the other.

THIS PAGE, TOP RIGHT
Triceratops specimen, removed from the bony plate (the frill) behind the skull of one of the largest fossilized dinosaur skulls ever discovered, shows the bone matrix (*orange background*), in addition to 30-micron-wide vascular channels (*pink*) and oblong bone formations (*yellow*). The skull specimen, photographed under polarized light by Ellen-Thérèse Lamm in the laboratory of renowned paleontologist Jack Horner at the Museum of the Rockies at Montana State University, is providing key evidence in studies examining radical changes in the dinosaur skull throughout the life of the animal.

THIS PAGE, BOTTOM
Skin cells from a patient with amyotrophic lateral sclerosis were reprogrammed to become stem cells that then differentiated into motor neurons, the cells afflicted in the disease. Gist Croft of Columbia University and Mackenzie Weygandt of Project ALS used an inverted fluorescent microscope to take snapshots of the motor neurons' 25-micron-wide nuclei (*green*) and their long, connecting fibers, or axons (*red*), to compare diseased cells with their healthy counterparts.





FACING PAGE

Water flea (*Daphnia atkinsoni*) sports a comblike crown of thorns (*green, spiny structure in head*) to make itself unappetizing to predators. The crown, which measures about 200 microns across, emerges in offspring of parents that sense a chemical signal emitted by the tadpole shrimp (*Triops cancriformis*). Jan Michels of Christian Albrecht University of Kiel in Germany, who won first prize, used confocal laser scanning microscopy to create the image. Exposed to the laser light of the microscope, a dye that stains the exoskeleton fluoresces green, and some of the internal tissues fluoresce on their own, including the compound eye, which turns blue and red.

THIS PAGE, TOP

Salmon embryos remained still long enough for a Mount Holyoke College undergraduate student to snap their picture. Haruka Fujimaki applied bright-field optics to capture an image of the larvae that she had raised as part of an Atlantic salmon stock-restoration project in western Massachusetts. The three larvae, with eyes measuring about two millimeters in diameter, had just hatched and were still attached to yolk sacs for nourishment.

THIS PAGE, BOTTOM

Extremities in this transgenic mouse embryo turned blue to reveal the activity of a protein called fibroblast growth factor, suggesting that the protein has a role in the growth of digits. Mohammad K. Hajihosseini of the University of East Anglia in England (and his collaborators Saverio Bellusci and Stijn De Langhe) photographed the embryo, which had inherited a transgenic "reporter gene" that gave rise to a blue stain when the growth factor gene was switched on.

More ...

SCI AM

Find a slide show with more images and watch stunning videos at **www.ScientificAmerican.com/dec2009**

For more information about the Olympus BioScapes competition, visit **www.olympusbioscapes.com**

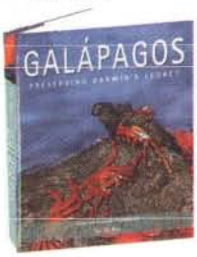
Science in Pictures ▪ Ocean Icon ▪ Silk Road Sojourn

BY KATE WONG

Feast your eyes and feed your brain with our favorite science books worthy of the coffee table. Topping our list are volumes commemorating the 200th anniversary of the birth of Charles Darwin and the 400th anniversary of the invention of the telescope.

GALÁPAGOS: PRESERVING DARWIN'S LEGACY

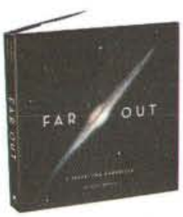
edited by Tui de Roy. Firefly Books, 2009 ($49.95)



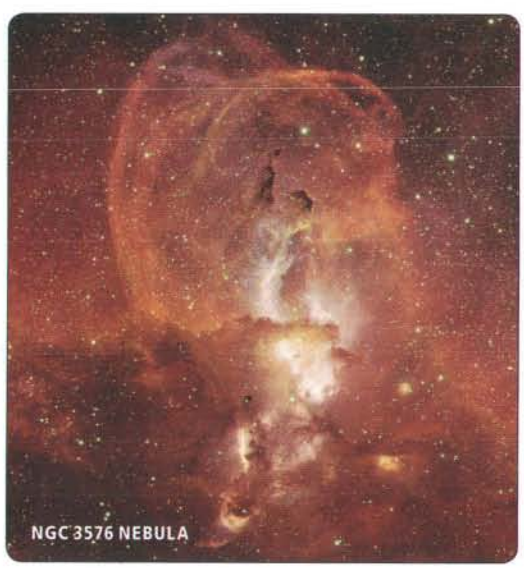
Editor and principal photographer Tui de Roy documents life on the islands that helped inspire Darwin's theory of evolution by natural selection. Essays by 30 experts cover such topics as the social behavior of the Galápagos hawk (*above*) and efforts to restore tortoise populations.

FAR OUT: A SPACE-TIME CHRONICLE

by Michael Benson. Abrams, 2009 ($55)



Journalist Michael Benson leads readers from our own Milky Way back in time and space to the earliest galaxies with this glorious collection of astronomical images from the finest ground- and space-based telescopes, as well as a few amateur astrophotographers.



NGC 3576 NEBULA

THE HEART OF THE GREAT ALONE: SCOTT, SHACKLETON, AND ANTARCTIC PHOTOGRAPHY

by David Hempleman-Adams, Emma Stuart and Sophie Gordon. Bloomsbury, 2009 ($47.50)

NO SMALL MATTER: SCIENCE ON THE NANOSCALE

by Felice C. Frankel and George M. Whitesides. Harvard University Press, 2009 ($35)

ALSO NOTABLE

BIOGRAPHIES

- **Perfect Rigor: A Genius and the Mathematical Breakthrough of the Century** by Masha Gessen. A biography of Grigory Perelman. Houghton Mifflin Harcourt, 2009 ($26)
- **The Passage to Cosmos: Alexander von Humboldt and the Shaping of America** by Laura Dassow Walls. University of Chicago Press, 2009 ($35)
- **Jacques Cousteau: The Sea King** by Brad Matsen. Pantheon, 2009 ($27.95)

- **Grace Hopper and the Invention of the Information Age** by Kurt W. Beyer. MIT Press, 2009 ($27.95)

OTHER NONFICTION

- **The Faith Instinct: How Religion Evolved and Why It Endures** by Nicholas Wade. Penguin Press, 2009 ($25.95)
- **Green Intelligence: Creating Environments That Protect Human Health** by John Wargo. Yale University Press, 2009 ($32.50)
- **Dinosaur Odyssey: Fossil Threads in the Web of Life** by Scott D. Sampson. University of California Press, 2009 ($29.95)
- **Mathletics: How Gamblers, Managers, and Sports Enthusiasts Use Mathematics in Baseball, Basketball, and Football** by Wayne L. Winston. Princeton University Press, 2009 ($29.95)
- **Elephants on the Edge: What Animals Teach Us about Humanity** by G. A. Bradshaw. Yale University Press, 2009 ($28)

EXHIBITS

- **Traveling the Silk Road: Ancient Pathway to the Modern World. November 14, 2009–August 15, 2010, at the American Museum of Natural History in New York City.**
- **The Accidental Mummies of Guanajuato. October 10–April 11, 2010, at the Detroit Science Center.**

13TH-CENTURY Persian ceramic bowl

TUI DE ROY (*hawk*); *FAR OUT: A SPACE-TIME CHRONICLE*, ABRAMS 2009 (*nebula*); COURTESY OF THE BROOKLYN MUSEUM (*bowl*)

Why did NASA decide to launch **space shuttles** *from weather-beaten Florida?*

Space historian **Roger D. Launius,** a senior curator at the Smithsonian National Air and Space Museum, provides an answer (as told to John Matson):

Florida was chosen as the starting point for U.S. manned missions—which began with the 1961 Project Mercury flights—for several reasons. One was that the location had to be on the coast, over the ocean, so falling debris or spent rocket boosters would not drop on inhabited places during ascent. The Atlantic coast is preferable because blasting off in an easterly direction allows the spacecraft to harness the rotation of the earth rather than fighting against it, which saves a lot of fuel for a rocket attempting to escape terrestrial gravity.

The second reason was that Florida is close to the equator, where the velocity of the earth's spinning surface is the greatest. The best launch site in the world right now is the spaceport that the European Space Agency has in French Guiana, about five degrees north of the equator.

Merritt Island, where the Kennedy Space Center stands, already had good logistics when the spaceport was built. It had decent roads because there was already a navy and an army base nearby. But the population density was basically nonexistent, so you could build what you wanted. The U.S. did have lower-latitude options such as Puerto Rico and Hawaii, but those places are more difficult to reach, which may have diminished their appeal.

Last, it is important to remember that even though Florida has the turbulent climate of the subtropics, weather is an issue in most places. The middle of the country has Tornado Alley. In the South there are hurricanes. Wherever you go, there are always issues.

Now that it is in place, I think Kennedy is it for the foreseeable future in terms of manned spaceflight in the U.S. The infrastructure that has been built there would be very expensive to replicate somewhere else. ■

HAVE A QUESTION?... *Send it to experts@SciAm.com or go to* **www.ScientificAmerican.com/asktheexperts**

SPACE SHUTTLE *Endeavour,* July 15, 2009

AFP/GETTY IMAGES

STATEMENT OF OWNERSHIP, MANAGEMENT, AND CIRCULATION *1.* Publication title: Scientific American. *2.* Publication number: 509-530. *3.* Filing date: 9/27/2009. *4.* Issue frequency: monthly. *5.* Number of issues published annually: 12. *6.* Annual subscription price: U.S. and its possessions, 1 year, $34.97; Canada, 1 year, $49; all other countries, 1 year, $55. *7.* Complete mailing address of known office of publication: Scientific American, Inc., 75 Varick Street, 9th Floor, New York, NY 10013-1917. *7a.* Contact person: Karen Dawson; telephone: 212-726-9369. *8.* Complete mailing address of the headquarters or general business office of the publisher: Scientific American, 75 Varick Street, 9th Floor, New York, NY 10013-1917. *9.* Full names and complete mailing address of publisher, editor and managing editor: Publisher, Bruce Brandfon, Scientific American, 75 Varick Street, 9th Floor, New York, NY 10013-1917, New York, NY 10013-1917. Editor, Mariette DiChristina, Scientific American, 75 Varick Street, 9th Floor, New York, NY 10013-1917. Managing Editor, Ricki L. Rusting, Scientific American, 75 Varick Street, 9th Floor, New York, NY 10013-1917. *10.* Owner: Scientific American, Inc., 75 Varick Street, 9th Floor, New York, NY 10013-1917; Holtzbrinck Publishing Holdings Limited Partnership, 175 5th Avenue, 19th Floor, New York, NY 10010: (*a*) Holtzbrinck Publishing Group, Inc. (General Partner), 175 5th Avenue, 19th Floor, New York, NY 10010; (*b*) Georg von Holtzbrinck GmbH & Co. (Limited Partner), Gaensheidestrasse 26, 70184 Stuttgart, Germany. *11.* Known bondholders, mortgagees and other security holders owning or holding 1 percent or more of total amount of bonds, mortgages or other securities: none. *12.* Tax status: not applicable. *13.* Publication title: Scientific American. *14.* Issue date for circulation data below: September 2009. *15.* Extent and nature of circulation; paid consumer magazine: a. Total number of copies (net press run): average number of copies of each issue during preceding 12 months: 918,814; number of copies of single issue published nearest to filing date: 928,437. b. Paid circulation (by mail and outside the mail): (1) mailed outside-county paid subscriptions stated on PS Form 3541 (include paid above nominal, advertiser's proof and exchange copies): average number of copies of each issue during preceding 12 months: 493,425; number of copies of single issue published nearest to filing date: 442,472. (2) mailed in-county paid subscriptions stated on PS Form 3541 (include paid distribution above nominal rate, advertiser's proof copies and exchange copies): average number of copies of each issue during preceding 12 months: 0; number of copies of single issue published nearest to filing date: 0. (3) paid distribution outside the mail, including sales through dealers and carriers, street vendors, counter sales and other paid distribution outside USPS®: average number of copies of each issue during preceding 12 months: 180,861; number of copies of single issue published nearest to filing date: 250,952. (4) paid distribution by other classes of mail through the USPS (e.g., First-Class Mail®): average number of copies of each issue during preceding 12 months: 0; number of copies of single issue published nearest to filing date: 0. c. Total paid distribution (sum of 15b (1), (2), (3) and (4)): average number of copies of each issue during preceding 12 months: 674,286; number of copies of single issue published nearest to filing date: 693,424. d. Free or nominal rate distribution (by mail and outside the mail): (1) free or nominal rate outside-county copies included on PS Form 3541: average number of copies of each issue during preceding 12 months: 17,157; number of copies of single issue published nearest to filing date: 57,008. (2) free or nominal rate in-county copies included on PS Form 3541: average number of copies of each issue during preceding 12 months: 0; number of copies of single issue published nearest to filing date: 0. (3) free or nominal rate copies mailed at other classes through the USPS (e.g., First-Class Mail): average number of copies of each issue during preceding 12 months: 0; number of copies of single issue published nearest to filing date: 0. (4) free or nominal rate distribution outside the mail (carriers or other means): average number of copies of each issue during preceding 12 months: 16,000; number of copies of single issue published nearest to filing date: 16,000. e. Total free or nominal rate distribution (sum of 15d (1), (2), (3) and (4)): average number of copies of each issue during preceding 12 months: 33,157; number of copies of single issue published nearest to filing date: 73,008. f. Total distribution (sum of 15c and 15e): average number of copies of each issue during preceding 12 months: 707,443; number of copies of single issue published nearest to filing date: 766,432. g. Copies not distributed (see instructions to publishers #4 (page #3)): average number of copies of each issue during preceding 12 months: 211,371; number of copies of single issue published nearest to filing date: 162,005. h. Total (sum of 15f and 15g): average number of copies of each issue during preceding 12 months: 918,814; number of copies of single issue published nearest to filing date: 928,437. i. Percent paid (15c divided by 15f times 100): average number of copies of each issue during preceding 12 months: 95.3%; number of copies of single issue published nearest to filing date: 90.5%. *16.* Publication of statement of ownership is required. Will be printed in the December 2009 issue of this publication. *17.* I certify that all information furnished above is true and complete. I understand that anyone who furnishes false or misleading information on this form or who omits material or information requested on the form may be subject to criminal sanctions (including fines and imprisonment) and/or civil sanctions (including civil penalties). Signature and title of Editor, Publisher, Business Manager, or Owner: (signed) Michael Florek, Vice President, General Manager. Date: 10/1/2009.

Crack Research

One man's long, noisy, asymmetrical adventure gets him a high five

BY STEVE MIRSKY

The latest physical anthropology research indicates that the human evolutionary line never went through a knuckle-walking phase. Be that as it may, we definitely entered, and have yet to exit, a knuckle-cracking phase. I would run out of knuckles (including those on my feet) trying to count how many musicians wouldn't dream of playing a simple scale without throwing off a xylophonelike riff on their knuckles first. But despite the popularity of this practice, most known knuckle crackers have probably been told by some expert—whose advice very likely began, "I'm not a doctor, but ..."—that the behavior would lead to arthritis.

One M.D. convincingly put that amateur argument to rest with a study published back in 1998 in the journal *Arthritis & Rheumatism* entitled "Does Knuckle Cracking Lead to Arthritis of the Fingers?" The work of sole author Donald Unger was back in the news in early October when he was honored as the recipient of this year's Ig Nobel Prize in Medicine.

The Igs, for the uninitiated, are presented annually on the eve of the real Nobel Prizes by the organization Improbable Research for "achievements that first make people laugh, and then make them think." In Unger's case, I thought about whether his protocol might be evidence that he is obsessive-compulsive. From his publication: "For 50 years, the author cracked the knuckles of his left hand at least twice a day, leaving those on the right as a control. Thus, the knuckles on the left were cracked at least 36,500 times, while those on the right cracked rarely and spontaneously."

Unger undertook his self and righteous research because, as he wrote, "During the author's childhood, various renowned authorities (his mother, several aunts and, later, his mother-in-law [personal communication]) informed him that cracking his knuckles would lead to arthritis of the fingers." He thus used a half-century "to test the accuracy of this hypothesis," during which he could cleverly tell any unsolicited advice givers that the results weren't in yet.

Finally, after five decades, Unger analyzed his data set: "There was no arthritis in either hand, and no apparent differences between the two hands." He concluded that "there is no apparent relationship between knuckle cracking and the subsequent development of arthritis of the fingers." Evidence for whether the doctor himself was cracked may be that he traveled all the way from his California home to Harvard University to pick up his Ig Nobel Prize in person.

Actually other scholarly studies of the phenomenon had been done. Responding to the Unger paper, Robert Swezey, M.D., wrote to the journal to report that his own 1975 study—coauthored by his then 12-year-old son in an apparent attempt to get the kid's grandma to stop the kvetching over the cracking—also found no crack case for arthritis. Swezey further consulted Rand Corporation statistician John Adams, who noted that "it appears that the [Unger] study was not blinded. Blinding would only be possible if the investigator didn't know left from right. This is not likely since studies indicate that only 31 percent of primary care physicians don't know left from right."

The knuckle kerfuffle reminded me that Stanford University bone development expert David Kingsley got dragged into this field a few years back when his son's fourth grade class asked him if cracking was bad for you. He challenged them to come up with ways to find out while he searched the medical literature. "One kid said that we could divide the room in half," he recalled, "and some of us could really crack our knuckles a lot and the others couldn't, and we could see whether we end up with arthritis—an intervention experiment. I said that this was a great idea. The only problem was that it might take 20 years." Or even 50.

"Then a budding epidemiologist said you could go to old folks homes," Kingsley continued, "and ask everybody if they cracked their knuckles or not and then see whether they had arthritis. And that was exactly the kind of study that I had been able to find." In fact, two such studies did exist, the Swezey work that used 28 nursing home residents and a 1990 paper that examined 300 outpatients. Neither found an increased arthritis incidence among the crackers. So Unger probably could have stopped his study early. Nevertheless, he deserves a big hand. ■

PHOTOGRAPH BY FLYNN LARSEN; ILLUSTRATION BY MATT COLLINS